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PB-299 270

Performance Evaluation of an Electrostatic Precipitator Installed on a Copper Smelter Reverberatory Furnace

Southern Research Inst, Birmingham, AL

Prepared for

Industrial Environmental Research Lab Cinninnati, OH

Jun 79

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-79-119
June 1979

Research and Development

PB 299270

EPA

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TECHNICAL REPORT DATA

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1. REPORT NO. EPA-600/2-79-119	2.	3. RECIPIENT'S ACCESSION NO. PB299270
4. TITLE AND SUBTITLE Performance Evaluation of an Electrostatic Precipitator Installed on a Copper Smelter Reverberatory Furnace		5. REPORT DATE June 1979 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Anonymous		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute 2000 Ninth Avenue Birmingham, Alabama 35205		10. PROGRAM ELEMENT NO. 1AB604 11. CONTRACT/GRANT NO. R-804955
12. SPONSORING AGENCY NAME AND ADDRESS Industrial Environmetal Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA/600/12

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report describes tests performed on the electrostatic precipitator installed on the copper reverberatory furnace at the Kennecott Copper Corporation smelter at Hayden, Arizona. These tests provided data on the chemical characterization of particulates, noncondensables, and gases in addition to operating and performance measurements of electrical parameters, particle size, voltage-current distribution, and resistivity. Efforts were also made to develop computer simulations of ESP performance and to evaluate overall performance of the control device. The operation of the ESP was erratic, and other unavoidable restraints on the sampling program prevented acquisition of reliable data to evaluate representative performance of the ESP. Nevertheless, analysis of the data shows the types of information which can be obtained in evaluation of control devices if the test locations can be utilized to obtain data representative of normal "on stream" operations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Exhaust emissions Smelting Trace elements Pollution Electrostatic precipitators Particle size distribution	Air pollutant emissions Air pollutant control Copper smelter	68 A

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 177
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE A09-A01

EPA Form 2220-1 (Rev. 4-77)

☆ U. S. GOVERNMENT PRINTING OFFICE: 1979 — 657-060/5314

EPA-600/2-79-119
June 1979

PERFORMANCE EVALUATION OF AN ELECTROSTATIC PRECIPITATOR INSTALLED ON A COPPER SMELTER REVERBERATORY FURNACE

by

Southern Research Institute
Birmingham, Alabama 35205

Grant No. R-804955

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report presents the findings of an investigation of air pollutant emissions from the reverberatory furnace pollution control system at a primary copper smelter. The study was performed to assess the degree of particulate emissions control and control problems associated with the application of electrostatic precipitators in the nonferrous metals production industry. The results are being used within the Agency's Office of Research and Development as part of a larger effort to define the potential environmental impact of emissions from this industry segment and the need for improved controls. The findings will also be useful to other Agency components and the industry in dealing with environmental control problems. The Metals and Inorganic Chemicals Branch of the Industrial Pollution Control Division should be contacted for any additional information desired concerning this program.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report describes tests performed during the period January 11-16, 1977, on the electrostatic precipitator installed on the copper reverberatory furnace at the Kennecott Copper Corporation smelter at Hayden, Arizona. These tests provided data on the chemical characterization of particulates, noncondensables, and gases in addition to operating and performance measurements of electrical parameters, particle size, voltage-current distribution, and resistivity. Efforts were also made to develop computer simulations of ESP performance and to evaluate overall performance of the control device.

The operating condition of the reverberatory furnace was normal (with one major exception); however, the operation of the ESP was erratic, and other unavoidable restraints on the sampling program prevented acquisition of reliable data to evaluate representative performance of the ESP. Nevertheless, analysis of the data shows the types of information which can be obtained in evaluation of control devices if the test locations can be utilized to obtain data representative of normal "on stream" operations.

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ACKNOWLEDGMENTS

The cooperation of the personnel at Kennecott is gratefully acknowledged in the conduct of this research test program. Specifically we appreciate the assistance of Mr. K. H. Matheson, Jr., General Manager, and Messrs. J. S. Nebeker, Clint Fitch, Mike Kearney, and Joe Mortimer. We also acknowledge the assistance of personnel from Radian Corporation, particularly Messrs. Klaus Schwitzgebel and Bob Collins.

SECTION 1

SUMMARY AND CONCLUSIONS

During the period of January 11-16, 1977, Southern Research Institute, and Radian Corporation (as a subcontractor) conducted tests to evaluate the performance of the electrostatic precipitator installed on the copper reverberatory furnace at the Kennecott Copper Corporation's Ray Mines smelter located at Hayden, Arizona. Southern Research Institute and Radian Corporation collaborated on collection of data to characterize the chemical species in the inlet and outlet to the precipitator with respect to particulates, noncondensables, and gases. Southern Research Institute also collected smelter and precipitator operating data including electrical operating data for the precipitator, voltage-current characteristics, resistivity measurements, and particle size measurements including characterization of the overall and particle-size control efficiency. Computer simulations of the performance of the electrostatic precipitator were also made using the computer systems model developed at Southern Research Institute under the sponsorship of the U. S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, N. C.

Sections 2, 3 and 4 of this report describe the overall process, test facility, and test program. Section 5 outlines the results of the various chemical analyses, and Sections 6 and 7 present information on the overall performance of the precipitator. Section 8 describes the computer simulation efforts. Supporting data with detailed reverberatory operating data, analytical procedures, and cascade impactor data are presented in the Appendices.

The primary objectives of the test program were to evaluate the "on stream" performance of an electrostatic precipitator associated with operation of a copper reverberatory furnace and to evaluate methods for determining the chemical species in the particulate, condensable, and non-condensable emissions from the reverb and the precipitator.

Operation of the reverberatory furnace during the test period of January 11-16, 1977, was considered "normal" except for occasional minor interruptions in converter operations and a major reverb shut-down on January 13. The feed to the reverb was primarily a partially roasted calcine containing recycled converter slags and dusts. During the test period, the reverb was fired with No. 2 fuel oil. Typically, the reverb was charged at fifteen-minute intervals, slag and matte were tapped periodically, and fettling was added intermittently. All of these cyclic and intermittent operations cause excursions in both the reverb temperature and the effluent that affect the gas flow and particulate distribution into the precipitator. However, these variations are normal for a typical copper reverberatory furnace.

To evaluate the performance of the precipitator, gas and particulate test measurements were made at the inlet and outlet of the precipitator and at the stack, using isokinetic methods for collection of representative particulate, condensable, and non-condensable samples.

The electrical condition and operation of the precipitator power supplies were erratic during the test period with at least a part of the power being off during the entire test period. Further, the voltage-current data indicated anomalous and less than optimal behavior on several occasions, so that any data relative to normal operation of the ESP are highly questionable and are not necessarily representative of typical operation of this precipitator.

In addition to the electrical malfunctions which precluded collection of reliable and representative electrical operating data, sampling in both the inlet and outlet ducts presented major difficulties that affected the reliability of the particulate and gas measurements and analyses. For example, the sampling ports at the inlet were located approximately one meter from both upstream and downstream flow disturbances. (Note: The location was dictated by the physical configuration and accessibility). Also, except for measurements in the stack, only single point readings (no traverses) were made at either the inlet or outlet sample locations. These restraints necessarily affect the quality of the data collected and prevent any conclusive judgement of normal precipitator performance. Further, there was apparently an excessive in-leakage of air to the precipitator (about 40% of the inlet flow) which further complicated any significant analysis of performance data.

In spite of the preceding limitations, the test data have been analyzed and the results are presented in this report. Some of the observations based on the tests are summarized below:

1. Most of the major chemical elements and many of the minor elements present in the gas stream were removed at efficiencies in excess of 90%, based on chemical analyses. Elements removed at greater than 90% were copper, iron, aluminum, lead, zinc, and molydenum (present at the inlet at concentrations greater than

10 mg/m^3); and cadmium, chromium, nickel, antimony, and selenium (present at less than 10 mg/m^3).

2. Three elements (arsenic, mercury, and fluorine) were not effectively removed by the precipitator at normal operating temperatures (260°C or 500°F). No significant increase in particulate collection of these elements was observed by decreasing the temperature (of an out-of-stack filter) to 120°C (250°F).

3. Electrical conditions were highly variable during the test period, and current densities in specific fields varied from day to day.

4. Particulate resistivity was not limiting the operating characteristics of the precipitator.

5. Collection efficiency varied from one test to another; however, most of the data showed collection efficiencies greater than 95%.

SECTION 2

PROCESS DESCRIPTION

A simplified flow diagram of the smelting system for the Kennecott smelter at Hayden, Arizona is shown in Figure 1. Copper concentrates (containing recycled converter slag and dust), precipitates, and lime-silica flux are blended together as a dry feed to a single fluid-bed roaster operated at about 1150°F. In the roaster (or reactor), the concentrates are partially roasted to obtain calcines for feed to the reverberatory furnace and an SO_2-rich gas for feed to the sulfuric acid plant.

The roaster underflow calcine, the roaster overflow calcines from the cyclones, and various dusts from gas coolers, waste-heat boilers, and precipitators are combined to provide the charge to the reverberatory furnace. Fettling (miscellaneous slags or sand) are also added to the reverb as needed for special cooling. The nominal operating temperature of the reverb is about 2800°F, but some variations result from intermittent charging (about every fifteen minutes), slag skimming, and matte tapping. The reverb at Hayden may be either gas or oil fired.

The primary functions of the reverberatory furnace are melting of the mineral charge and separation of the molten charge into a slag waste and a copper-bearing matte. The slag is periodically skimmed out of the reverb for disposal, and the molten matte is periodically tapped from the bottom of the reverb and transferred by ladles to one of the three Pierce-Smith converters. Off-gases from the reverb are sent to two waste-heat boilers and then to the electrostatic precipitator before being exhausted to the atmosphere through a 600-ft stack.

The matte from the reverb is transferred to one of the converters where silica flux is added, and the resultant mixture is air blown to obtain a copper-rich iron-silica slag which is removed from the converter, slow cooled, and then returned to the crushing/flotation/concentrating circuit. After removal of slag from the converter, the remaining molten mass is air blown to convert the residual copper sulfide or "white metal" to molten copper or blister copper which is then transferred to the anode furnace for casting. Off gases from the converter are cooled, and dusts are removed in a Peabody scrubber before the SO_2-rich gases are sent to the acid plant. Recovered convertor dusts are recycled to the concentrate plant.

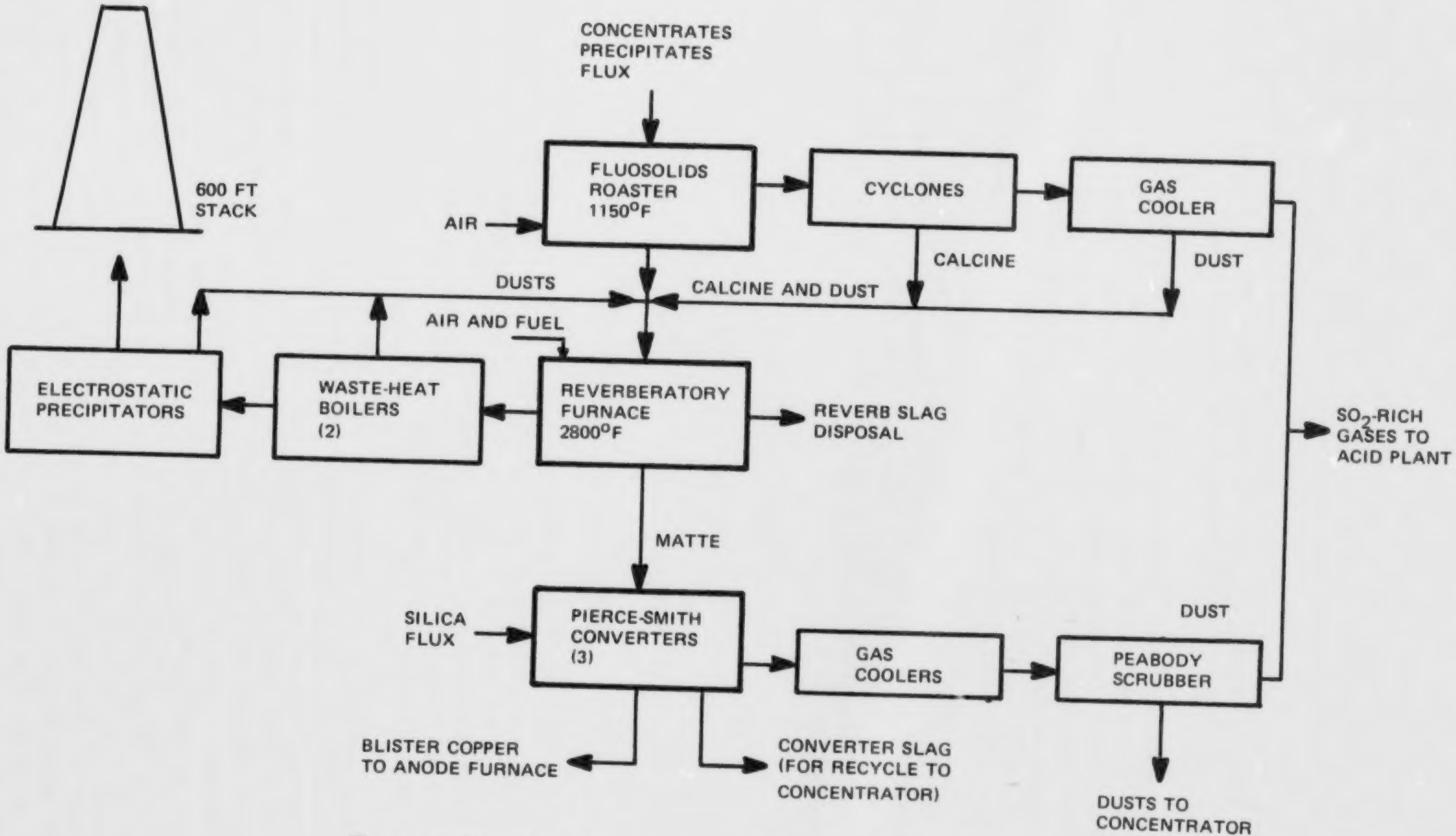

Figure 1. Simplified Flow Diagram of Copper Smelter.

During the test period of January 11-16, 1977, the roaster, reverberatory furnace, and converters were operated under moderately stable conditions, except for a major reverb shut-down on January 13 and minor interruptions in converter operations. Operational data for the test period are summarized in Table 1 and indicate that the overall smelter operation was reasonably consistent during the period, recognizing the normal cyclic discontinuities of reverb and converter operations.

The reverberatory furnace was fired exclusively with No. 2 fuel oil; no natural gas was used. The nominal temperature of the reverberatory furnace was reported to be 2800°F, however, actual temperatures measured near the feed-end of the reverb generally ranged from 2500 to 2800°F with typical intermittent decreases of 200 to 300°F with each charge cycle. Temperature profiles for the test period are shown in the Appendix, Figures A-13 to A-18.

A schematic diagram of the reverberatory furnace system is shown in Figure 2. Typical average operating conditions for the reactor (roaster) and reverberatory furnace during the January 12-16 tests were:

Reactor (roaster):

Dry feed = 60 tons/hr
Air feed = 15,000 CFM
Temperature = 1150°F

Reverberatory furnace:

Fuel oil = 30 gal/min
Calcine charge = 15 tons/charge @ 15 minute intervals
Fettling added = 0.5-1.0 ton/hr (intermittent)
Slag tapped = 11-12 tons/hr (intermittent)
Matte tapped = 2 ladles/hr (intermittent)
Temperature = 2500-2800°F

The discontinuities in operation of the reverberatory furnace are normal for copper smelting, and it is recognized that surges are encountered which affect downstream operations such as the waste heat boilers and the electrostatic precipitator. Removal of slag and tapping of matte cause relatively minor downstream perturbations; however, the periodic charging of feed to the reverb results in significant downstream surges in both gas temperature and composition (including particulate loading). The results of these reverb surges are illustrated in Figures A-13 to A-18 which show reverb temperatures and are also confirmed in Figure A-21 which gives a typical waste-heat boiler profile. For example, the steam temperature shows a fluctuation of 20-30°F that is coincident with the periodic charging of the reverb at fifteen minute intervals. Similar perturbations must necessarily be reflected in the electrostatic precipitator; however, the effects would probably be lessened by damping from the waste-heat boilers and the balloon-flue leading to the precipitator.

Based on the data obtained from the Hayden smelter, it appears that the operation of the reverberatory furnace during the period January 11-16, 1977, was typical of normal operations (except for the failure on January 13), and variations encountered downstream were typical of normal "on stream" reverb operation.

TABLE 1. SMELTER OPERATING DATA*

1. Dry Feed to Reactor (tons/shift)

Date	A	B	C	Avg.
1/11	464	484	455	467
1/12	471	477	477	475
1/14	460	492	448	467
1/15	478	445	480	468
1/16	480	497	503	493

Average feed rate = 60 tons/hr

2. Flux Added to Concentrate

Date	Tons
1/11	25
1/12	41
1/14	30
1/15	28
1/16	30
Avg.	30.8

3. Fettling to Reverb

Date	Tons
1/11	18
1/12	20
1/14	10
1/15	12
1/16	26
Avg.	17.2

4. Slag Removed (tons)

Date	Reverb	Converter
1/11	245	498**
1/12	212	620
1/14	318	647
1/15	206	629
1/16	373	-
Avg.	271	599

5. Ladles of Matte Produced

1/11	48
1/12	51
1/14	47
1/15	48
1/16	43
Avg.	47.4

6. Fuel Oil Burned (gal/day)

1/11	42,904
1/12	41,261
1/14	43,606
1/15	43,461
1/16	39,881
Avg.	42,223

7. Roaster (Reactor) Temperature = 1150 ± 100°F

8. Reverberatory Furnace Temperature = Nominal 2800°F

9. Reverberatory Gas Flow = 13,500 CFM (estimated)

10. Roaster (Reactor) Air Flow = Nominal 15,000 CFM

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* See Figures A-1 to A-20 for daily operating charts.

** No. 3 converter not operating.

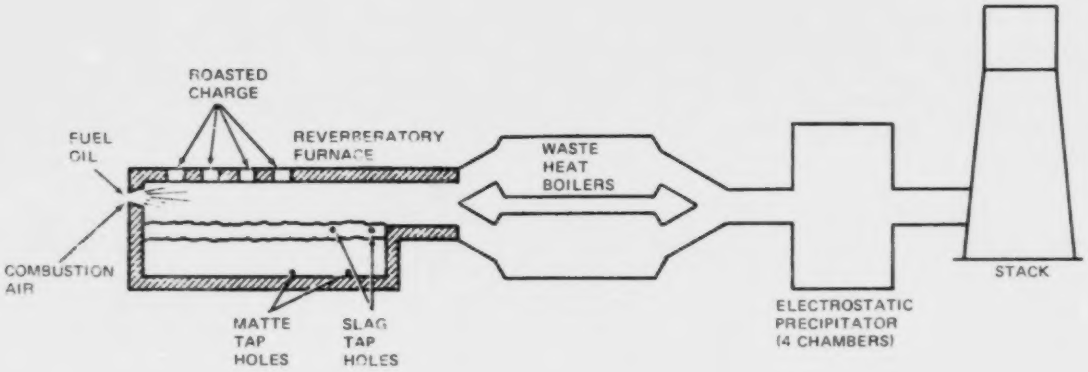

Figure 2. Reverberatory Furnace Schematic

SECTION 3

TEST FACILITY

Figure 3 is a schematic which shows the precipitator layout and the sampling locations used during the test program. The inlet sampling ports (Test Point No. 1) were located in the inlet plenum adjacent to the entry to the No. 1 precipitator chamber; the outlet sampling ports (Test Point No. 2) were located in the duct between the precipitator and the stack; and the stack sampling ports (Test Point No. 3) were located at the 70 meter (230 ft) level with the four ports at 90° angles. Test Point No. 1 was approximately 1 m from both upstream and downstream flow disturbances and therefore was not regarded as a desirable sampling location.

The precipitator on which the tests were conducted is an old Koppers unit which has recently been upgraded for improved performance. Physically, the precipitator is divided into four chambers. Each chamber is equipped with dampers on the inlet and outlet. The dampers on the outlet side are closed during rapping to reduce reentrainment. Each chamber is closed for rapping for about five minutes every hour. During the rapping periods, all gas flow is handled by the three "on stream" chambers so that intermittent periodic flow surges (other than those resulting from reverb operations) of 33% are normal for the precipitator operation.

The total collection electrode area is 5,044 m^2 (54,300 ft^2) and was designed for a total gas flow of about 140 m^3/sec (300,000 ft^3/min) at 500°F. From these data, the design SCA is estimated to be 36 $m^2/(m^3/sec)$ or 181 $ft^2/(1000\ ft^3/min.)$ Actual inlet flows during the test period averaged 73.4 m^3/sec (155,500 ft^3/min) at 473°F and ranged from 68 m^3/sec (143,850 ft^3/min) to 79 m^3/sec (168,000 ft^3/min) which would give an actual SCA of of about 70 $m^2/(m^3/sec)$ or 350 $ft^2/(1000\ ft^3/min)$. Other descriptive parameters for the precipitator are shown in Table 2.

Electrically, the precipitator is divided into twelve sections which are energized by six power supplies as shown in Figure 3. As a part of recent modifications, the power supplies were rewired for full wave operation, and transformer secondary current meters were installed, in addition to the current and

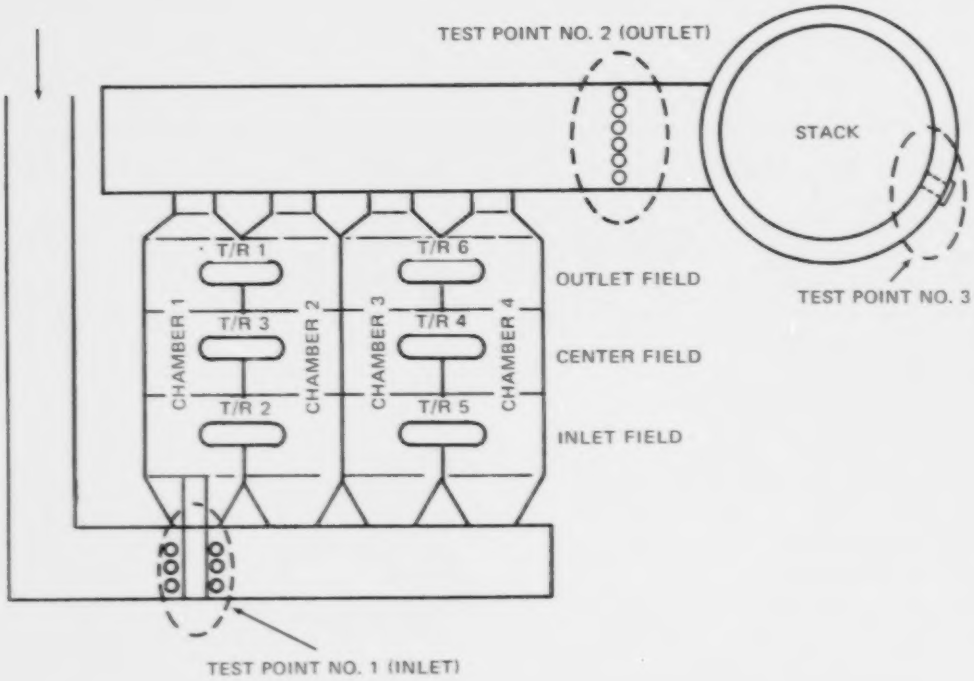

Figure 3. Layout of the precipitator showing sampling locations.

TABLE 2. ELECTROSTATIC PRECIPITATOR DESCRIPTIVE PARAMETERS MODIFIED KOPPERS INSTALLATION ON KENNECOTT'S HAYDEN REVERB

Item	Metric	English
Collection electrode area (4 chambers)	5,044 m^2	54,300 ft^2
Each T/R set area (6 sets)	840 m^2	9,050 ft^2
No. of fields per chamber	3	3
Collection electrode spacing	0.254 m	10 in.
Collection electrode dimensions	2.29 x 6.10 m	7.5 x 20 ft
Corona Electrode dimensions (square wire)	0.397 cm	0.15625 in.
Corona electrode spacing (parallel to flow)	0.152 m	6 in.
Number of gas passages (total	60	60
Gas passage length (active)	6.86 m	22.5 ft
Volume flow rate (design)	140 m^3/sec	300,000 ft^3/min
Actual flow rate (average)	73.4 m^3/sec	155,500 ft^3/min
Design temperature	260°C	500°C
Design efficiency	95%	95%
Design specific collection electrode area (SCA)	36 $m^2/(m^3/sec)$	181 $ft^2/(1000\ ft^3/min)$
Actual specific collection electrode area (SCA)	70 $m^2/(m^3/sec)$	350 $ft^2/(1000\ ft^3/min)$

voltage meters which are on the primary side of the power supply transformers. During the test period, voltage dividers were installed to allow secondary voltage measurements in addition to available primary voltage and primary and secondary current data. Representative power supply data obtained during the test period are shown in Table 3.

The power supply data in Table 3 illustrate that the electrical operation of the precipitator was very erratic. For the entire test period, TR No. 3 serving chambers 1 and 2 was partially or totally out of service. While a partial loss of one out of six TR sets would not materially affect the efficiency of the electrostatic precipitator, the erratic behavior of at least three of the remaining five would severely limit the value of any data collected regarding typical performance of the precipitator.

Therefore, data in this report should be used only with full recognition of the conditions existing when the tests were made. In brief, while the operation of the reverberatory furnace may be regarded as normal, the test locations (especially Test Point No. 1) were not ideal, and the electrical performance of the precipitator was inadequate to support a meaningful or significant evaluation of normal operation of expected efficiency for this installation.

TABLE 3. POWER SUPPLY LOG
KENNECOTT REVERBERATORY FURNACE PRECIPITATOR
HAYDEN, ARIZONA

Date	Time	T/R set	Primary voltage (V)	Primary current (A)	Primary power (kW)	Secondary voltage (kV)	Secondary current (mA)	Power (kW)	Spark rate (SPM)
1/12/77	0950	1	-	-	-	-	250	-	-
		2	-	-	-	-	80[1]	-	-
		3	-	-	-	-	60[1]	-	-
		4	-	-	-	-	160[2]	-	-
		5	-	-	-	-	250	-	-
		6	-	-	-	-	250	-	-
1/12/77	1300	1	-	-	-	-	240	-	-
		2	-	-	-	-	120	-	-
		3	-	-	-	-	70	-	-
		4	-	-	-	-	0	-	-
		5	-	-	-	-	250	-	-
		6	-	-	-	-	250	-	-
1/12/77	1800	1	280	70	19.6	-	240	-	0
		2	280	40	11.2	-	145	-	0
		3	205	26	5.3	-	82	-	0
		4	300	58	17.4	-	215	-	10
		5	135	60	8.1	-	230	-	0
		6	315	67	21.1	-	245	-	0
1/12/77	1910	1	285	65	18.5	49.3	240	11.8	0
		2	230	30	6.9	55.7	95	5.3	60
		3	210	25	5.3	43.6	87	3.8	10
		4	220-260	20-38	-	51.3	50-140	-	15
		5	<100	62	<6.2	-	260	-	0
		6	325	62	20.2	-	245	-	0
1/14/77	1030	1	300	64	19.2	44.3	250	11.1	10
		2	24	30	0.7	49.6	160	7.9	0
		3[3]	-	-	-	-	-	-	-
		4	250	27	6.8	47.7	80	3.8	0
		5	100	60	6.0	-	250	-	0
		6	350	55	19.3	-	220	-	0

- continued -

TABLE 3. (continued)

Date	Time	T/R set	Primary voltage (V)	Primary current (A)	Primary Power (kW)	Secondary voltage (kV)	Secondary current (mA)	Power (kW)	Spark rate (SPM)
1/14/77	1245	1	300	64	19.2	44.8	240	10.8	0
		2	240	20	4.8	48.2	60	2.9	0
		3[3]	-	-	-	-	-	-	0
		4	260	24	6.2	46.2	70	3.2	0
		5	-	62	-	-	250	-	0
		6	370	62	22.9	-	250	-	0
1/14/77	1445	1	280	60	16.8	44.4	220	9.8	100
		2	226	17	3.8	46.4	40	1.9	50
		3[4]	170	10	1.7	37.3	30	1.1	0
		4	220	17	3.7	43.5	50	2.2	10
		5	-	60	-	-	250	-	0
		6[5]	310	45	14.0	-	160	-	0
1/14/77	1740	1	270	52	14.0	44.3	190	8.4	125
		2	250	25	6.3	47.3	80	3.8	25
		3[4]	150	10	1.5	38.0	30	1.1	100
		4	210	15	3.2	45.9	40	1.8	10
		5	-	44	-	-	180	-	75
		6	270	32	8.6	-	100	-	0
1/15/77[6]	1015	1	170	14	2.4	37.0	30	1.1	0
		2	160	~5	0.8	42.8	10	0.4	Unstable
		3	160	~5	0.8	38.3	20	0.8	0
		4	170	12	2.0	41.4-45.0	15-20	~0.7	10-25
		5	-	58-62	-	-	240-260	-	Unstable
		6	220	16	3.5	-	50	-	Unstable
1/15/77[6]	1355	1	170	14	2.4	37.1	30	1.1	-
		2	180	10	1.8	41.8-45.6	10	0.4	~50
		3	160	10	1.6	39.1	30	1.2	0
		4	200	14	2.8	46.1	20	0.9	0-50
		5	-	58-62	-	-	250	-	0
		6	250	30	7.5	-	100	-	0-25

- continued -

TABLE 3. (continued)

Date	Time	T/R set	Primary voltage (V)	Primary current (A)	Primary Power (kW)	Secondary voltage (kV)	Secondary current (mA)	Power (kW)	Spark rate (SPM)
1/15/77[6]	1510	1	150	11	1.7	34.9	20	0.7	0
		2	150	<10	1.5	35.2-41.8	10	0.4	25-50
		3	160	10	1.6	37.9	20	0.8	25-50
		4	160	10	1.6	35.1-41.9	10	0.4	25-50
		5	70 ?	62	4.3	-	260	-	0
		6	285	40	11.4	-	135	-	20
1/15/77[6]	1740	1	130	~8	1.0	33.2	10	0.3	0
		2	130	<5	0.7	41.5	~5	0.2	25-50
		3	150	~5	0.8	37.3	20	0.7	0
		4	170	12	2.0	42.5	20	0.9	0-25
		5	80 ?	58-62	4.8	-	260	-	Unstable
		6	210	18	3.8	-	50	-	0-25
1/16/77[7]	1000	1	172	22	3.8	33.7	60	2.0	0
		2	165	13	2.1	36.3	33	1.2	0
		3	160	12	1.9	34.7	30	1.0	0
		4	220	27.5	6.1	41.0	85	3.5	0
		5	~90	60-62	5.5	-	250-260	-	0
		6	320	62.5	20.0	-	240	-	0
1/16/77[7]	1200	1	180	23	4.1	35.8	65	2.3	0
		2	190	14	2.7	40.3	40	1.6	0
		3	150	10	1.5	34.4	25	0.9	0
		4	240	29	7.0	44.4	90	4.0	0-10
		5	80 ?	60-62	0.5	-	250-260	-	0
		6	332	62.5	20.8	-	245	-	0

- continued -

TABLE 3. (continued)

Date	Time	T/R set	Primary voltage (V)	Primary current (A)	Primary Power (kW)	Secondary voltage (kV)	Secondary current (mA)	Power (kW)	Spark rate (SPM)
1/16/77[7]	1345	1	190	24	4.6	35.4	75	2.7	0-25
		2	190	14	2.7	-	40	-	0
		3	150	10	1.5	-	30	-	0
		4	217	39	8.5	45.0	135	6.1	0
		5[8]	215	19.5	4.2	42.5-43.2	80	3.4	0
		6	320	62	19.8	44.1	240	10.6	0
1/16/77[7]	1615	1	200	26	5.2	38.3	75	2.9	0
		2	190	15	2.9	-	40	-	0
		3	150	8	1.2	-	20	-	0
		4	260	38	9.9	45.2	120	5.4	0
		5	120	48-52	0.6	<9.5	210	2.0	Unstable
		6	310	49	15.2	45.5	180	8.2	0-25
		# 5 in manual	182	6	1.1	40.9	40	1.7	0

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1. Spark limited in manual operation.
2. Spark limited in automatic operation.
3. No. 3 TR off.
4. Center field of Chamber No. 2 off.
5. No. 6 TR placed in manual due to arcing in bus duct.
6. All TR's in manual, half of No. 3 off.
7. TR's 5 and 6 in auto, others manual, half of No. 3 off.
8. Voltage dividers moved from 2 and 3 to 5 and 6.

SECTION 4

TEST PROGRAM

The test program conducted at Kennecott's copper smelter at Hayden, Arizona on January 11-16, 1977, was primarily concerned with evaluation of the performance of the electrostatic precipitator following the reverbatory furnace.

The test program was carried out by Southern Research Institute and Radian Corporation as part of EPA Research Grant R80955, administered by U.S. EPA's Industrial Environmental Research Laboratory, Cincinnati, Ohio.

The primary objectives of the SoRI-Radian program were:

1. Characterization of the chemical species and phases at the inlet and outlet of the precipitator
    - a. Particulates - Radian and SoRI
    - b. Noncondensables - Radian and SoRI
    - c. Gas analysis (Orsat) - SoRI
2. Evaluation of precipitator operation
    - a. Electrical operating data - SoRI
    - b. Particle size measurements - SoRI
    - c. Voltage-current characterization - SoRI
    - d. Resistivity measurements - SoRI
    - e. Computer model simulation - SoRI

The sampling locations were shown earlier in Figure 3. The sampling schedule for the test period is shown in Table 4. Since the reverbatory furnace was not operational on January 13, no tests could be made on that date; however, the original test plan was extended an additional day to conduct all tests originally scheduled.

TABLE 4. SAMPLE PORT UTILIZATION FOR TEST PROGRAM

	Precipitator Inlet				Precipitator Outlet				Stack			
Date	Port	Time	Organization	Test	Port	Time	Organization	Test	Port	Time	Organization	Test
1/11/77	5	AM-PM	Radian	WEP								
					6	AM-PM	Radian	Vapor Train				
1/12/77					1	AM	SoRI	Orsat				
	1-2	PM	SoRI	Impactor	1	PM	SoRI	Trace element				
	3	PM	SoRI	Hi-Vol	2	AM-PM	SoRI	Impactor				
	4	AM	SoRI	Resistivity	3	AM-PM	SoRI	Impactor				
	4	PM	SoRI	Orsat	4	AM-PM	Radian	WEP				
	5	AM-PM	Radian	WEP								
	6	AM-PM	SoRI	Ultrafine	6	AM-PM	Radian	Vapor train				
1/13/77	Reverberatory furnace not operational. No tests conducted.											
1/14/77					1	AM	SoRI	Orsat				
	2	AM-PM	SoRI	Ultrafine	2	AM-PM	SoRI	Trace element	South	AM-PM	Radian	WEP
	2-3	AM-PM	SoRI	Impactor	3	AM-PM	SoRI	Impactor				
	4	AM	SoRI	Resistivity	4	AM-PM	SoRI	Impactor				
	4	PM	SoRI	Orsat	6	AM-PM	Radian	Vapor Train				
1/15/77					1	PM	SoRI	Orsat				
	1-2	AM-PM	SoRI	Impactor/ Ultrafine	2	AM-PM	SoRI	Ultrafine	North	AM-PM	Radian	WEP
	3	PM	SoRI	Impactor/Hi Vol	3	AM-PM	SoRI	Impactor				
	4	AM	SoRI	Resistivity	4	AM-PM	SoRI	Impactor				
	4	PM	SoRI	Orsat	5	AM-PM	Radian	WEP				
	5	AM-PM	Radian	WEP								
	6	AM-PM	SoRI	Trace element								
1/16/77					1	AM-PM	SoRI	Orsat				
	1-2	PM	SoRI	Impactor	2	AM-PM	SoRI	Ultrafine				
	3	PM	SoRI	Impactor	3	AM-PM	SoRI	Impactor				
	4	AM	SoRI	Resistivity	4	AM-PM	SoRI	Impactor				
	4	PM	SoRI	Orsat								
	6	AM-PM	SoRI	Trace Element								

SECTION 5

CHEMICAL ANALYSIS

TRACE ELEMENTS IN REVERBERATORY-FURNACE OFF-GASES

Sampling Methods

The task of sampling trace elements from gas streams entering and leaving the ESP was shared by Radian Corporation and Southern Research Institute. The objective in having two organizations participate in trace-element sampling was to obtain data by different procedures for comparative purposes. The sampling procedures employed by Radian had been used in characterizing emissions from various sources in the past; the procedures employed by the Institute, on the other hand, had had little previous utilization but offered the potential advantage of fractionating the sampled material as solids, condensables, and vapors.

Radian used three types of sampling trains, as described briefly below and in detail in Appendix B:

- One train was referred to as the "WEP" train, where the acronym stands for wet electrostatic precipitator. Sample gas was drawn through a Pyrex sampling nozzle, then through the WEP, and finally through a series of solution-filled impingers. Particulates and some vapors were collected in the WEP. Vapors escaping the WEP were caught in the impingers.

- Another train was specific for mercury vapor. Sample gas was drawn through aqueous hydrogen peroxide to remove sulfur dioxide and then through a plug of fine gold wire, which retained mercury by amalgamation.

- The third train was applicable for vapors in general. A glass-fiber filter inserted in the sampling duct removed particulates. Vapors passing through the filter were removed in a series of external impingers having the same contents as the impingers in the WEP train.

Southern Research Institute also used three types of sampling trains. The components of these trains are described briefly below and in detail in Appendix C:

- One train was used at the ESP inlet for collecting particulates and vapors. Three cyclone samplers in series for particulates were inserted in the sampling duct with a backup glass-fiber thimble. A glass-fiber filter was then mounted in an oven at 120°C (250°F) outside the duct to collect condensable vapors, and it was followed by a series of impingers to collect residual vapors. This sampling train is subsequently referred to as a "CFI" train (the letters designate cyclones, filters, and impingers, respectively).

- Another train—basically a simplification of the first—was used at the ESP outlet. Only one cyclone was inserted in the sampling duct, and it was followed by a backup glass-fiber filter disc instead of a glass-fiber thimble. This train is also referred to as a "CFI" train.

- The third train was for mercury vapor. Sample gas was drawn through a sodium carbonate bubbler to remove sulfur dioxide and then through acidified potassium permanganate to absorb the mercury. This train yielded results that were much lower than those obtained with the CFI trains. Later work in the laboratory showed that the absorption efficiency of the vapor train was poor. Thus, all of the data given in this report for mercury were based on the results obtained with the CFI trains.

Both Radian and the Institute collected samples at the inlet and outlet ducts of the ESP, at locations previously shown in Figure 3. In addition, Radian collected samples from the stack at the 70-m (230-ft) level. Composite samples of particulates and vapors were collected at the inlet and outlet of the ESP by both Radian (with the WEP train) and the Institute (with the CFI trains). Samples were collected at the stack location only by Radian, using the WEP train. Radian used the vapor train only at the ESP outlet, but Radian and the Institute collected mercury in the special trains for this element at both the inlet and outlet.

Because of the limited number of sampling ports available in the inlet and outlet ducts, both organizations sampled from single points at these locations. Sampling by traversing over a number of points at the inlet and outlet was not practical because of the need for operating other equipment in the limited number of sampling ports available. Especially at the inlet, the sampling location was not ideal, and the samples collected may not have been representative. The first plenum entering the ESP is located immediately following the inlet sampling points, and there was considerable uncertainty about the sampling velocity needed for isokinetic conditions. Also, the low gas velocity introduced the possibility of particulate stratification in the plane of the inlet sampling ports. The sampling points in the stack, on the other hand, were more nearly ideal. Here, Radian sampled at a series of points along the diameter of the stack.

Analytical Methods

Both Radian and the Institute determined the concentrations of 19 elements in the samples removed from the gas streams entering and leaving the ESP. These 19 elements were as follows:

Silver, Ag
Aluminum, Al
Arsenic, As
Gold, Au
Barium, Ba
Cadmium, Cd
Cobalt, Co
Chromium, Cr
Copper, Cu
Fluorine, F
Iron, Fe
Mercury, Hg
Molybdenum, Mo
Nickel, Ni
Lead, Pb
Antimony, Sb
Selenium, Se
Vanadium, V
Zinc, Zn

In general, sample analysis required two types of operations: (1) dissolution of materials collected in the solid state and (2) processing of solutions by one or more steps as required to obtain quantitative determinations of the individual elements. The procedures used by Radian and the Institute differed in a number of respects. Details are given in Appendix B for the methods used by Radian and in Appendix C for the methods used by the Institute. Some of the highlights of the experimental procedures are presented in the following paragraphs, however.

Procedures Used by Radian--

Solid matter collected in the WEP was treated by either of two methods. Perchloric acid digestion was used to dissolve samples to be analyzed for most of the elements at low concentrations. Lithium borate fusion was used as an alternative method for most of the elements at higher concentrations; the cooled melt was dissolved in hydrochloric acid and hot water.

Liquid samples from the WEP train (dissolved solids and original liquor) were combined prior to analytical processing. Similarly, the different kinds of solutions used in the impingers were combined prior to analysis.

Atomic absorption spectrophotometry was the most commonly used analytical tool. Some elements were determined by direct injection into a flame or graphite furnace. Others were first concentrated by extraction prior to determination by atomic absorption. Fluorine was one element not determined by atomic absorption; this element was determined with a fluoride ion-selective electrode. Selenium was another exception, being determined by a fluorometric procedure.

Procedures Used by the Institute--

Solid samples collected in cyclones were routinely dissolved by a procedure that involved a series of steps involving additions of nitric, sulfuric, and perchloric acids. A few samples in more abundant supply were treated by an alternative procedure involving attack first by aqua regia and then perchloric acid. Sodium hydroxide fusion was used to prepare samples for fluoride determination.

Solids collected on filters presented a special problem, since insufficient material was present for separation from the filter media. These samples were extracted from the filters by refluxing with aqua regia.

As a rule, the contents of the impingers were combined prior to further processing. Most of the elements were determined by atomic absorption. Fluorine was an exception, being determined with an ion-selective electrode as in Radian's procedure. Selenium was another exception, being determined fluorometrically as in Radian's work.

Analytical Results

Complete tabulations of the analytical results obtained by Radian and the Institute are given in Appendices B and C. Information abstracted from those tabulations is presented and discussed in the sections of this report immediately following.

Total Elemental Concentrations--

The total concentrations of the trace elements occurring as particulate and vapor that were found at the inlet and outlet sides of the ESP are given in Tables 5 and 6, respectively. These data are based on the results obtained by the individual organizations for samples collected on the indicated dates.

The data obtained by both Radian and the Institute show wide variations from day to day. These variations may be due to deficiencies in sampling or analysis; however, there is no way to assess the relative importance of such deficiencies and actual changes in emission rates resulting from process variations, since the nature of the reverberatory furnace and precipitator operations were such that significant changes in emission rates would be expected.

TABLE 5. TOTAL CONCENTRATIONS OF TRACE ELEMENTS AT THE ESP INLET DUCT

Date	Jan. 12	Jan. 14	Jan. 15	Jan. 15	Jan. 16
Sampling train	WEP	WEP	WEP	CFI	CFI
Element	Concentration,[a] mg/m³				
Ag	0.46	0.18	0.45	0.13	0.32
Al	30	53	16	26	82
As	12	28	12	13	23
Au	0.001	0.005	0.001	<0.001	<0.001
Ba	<7.0	<0.7	<0.1	0.070	0.38
Cd	4.3	13	2.3	1.2	9.4
Co	0.064	0.47	0.071	0.05	0.08
Cr	0.33	1.0	0.55	0.52	0.88
Cu	250	590	270	330	960
F	86	82	57	34	60
Fe	280	710	270	250	840
Hg	–[b]	0.0011[c]	0.016[c]	0.011	0.021
Mo	28	43	13	13	31
Ni	0.22	1.6	0.28	0.49	1.5
Pb	25	36	14	4.4	25
Sb	2.8	3.4	1.8	1.0	3.5
Se	0.64	2.0	0.76	1.0	3.0
V	0.32	0.43	0.47	0.07	0.17
Zn	27	5.7	22	23	54

a. Calculated for 21°C (70°F) and 760 mmHg.

b. Not determined.

c. Determined with Radian's special train for mercury vapor.

TABLE 6. TOTAL CONCENTRATIONS OF TRACE ELEMENTS AT THE ESP OUTLET DUCT AND STACK

Date	Jan. 12	Jan. 12	Jan. 14, 15
Sampling train	WEP	CFI	WEP
Location	Duct	Duct	Stack
Element	Concentration,[a] mg/m^3		
Ag	0.093	0.01	0.14
Al	0.91	0.87	0.57
As	8.4	6.8	8.5
Au	<0.00004	<0.001	<0.00022
Ba	<0.05	<0.01	<0.05
Cd	0.20	0.14	0.23
Co	0.0020	<0.02	0.0034
Cr	0.069	0.03	0.041
Cu	3.6	8.1	7.3
F	69	21	47
Fe	2.3	3.2	3.4
Hg	–[b]	0.008	0.0018[c]
Mo	0.80	0.61	1.1
Ni	0.086	0.04	<0.003
Pb	0.13	0.35	0.91
Sb	0.16	0.15	0.18
Se	0.011	0.07	0.0027
V	0.38	<0.01	0.43
Zn	1.5	2.4	1.9

a. Calculated for 21°C (70°F) and 760 mmHg.

b. Not determined.

c. Determined with Radian's special train for mercury vapor.

Samples were collected simultaneously by Radian and the Institute at the inlet of the ESP on January 15 and at the outlet on January 12. A comparison of the individual results obtained for these samples shows reasonable agreement only in rare instances. The differences may be due to sampling or analytical deficiencies, or they may also reflect actual differences in concentrations at the points used for sampling.

To facilitate observations from the data, average concentrations at the inlet and outlet were calculated and are presented in the second and third columns of Table 7. Averaging cannot be entirely justified, for equal weight cannot be placed on the significance of the individual sets of analytical data. This point is illustrated, for example, by the fact that data for the outlet duct were obtained at single points on 1 day whereas the data for the stack were obtained by a traversing procedure on 2 days. Even so, the following conclusions appear to be valid:

- Inlet concentrations
  - Copper and iron were the elements having the highest concentrations, around 500 mg/m^3.
  - Six elements ranked next (aluminum, arsenic, fluorine, molybdenum, lead, and zinc) with concentrations between 10 and 100 mg/m^3.
  - Three elements were the next most abundant (cadmium, antimony, and selenium) with concentrations between 1 and 10 mg/m^3.
  - Seven of the other eight elements (silver, gold, cobalt, chromium, mercury, nickel, and vanadium) occurred at concentrations below 1 mg/m^3. The remaining element—barium—probably was also below this level.
- Outlet concentrations
  - Fluorine was the most abundant element, at a concentration of about 50 mg/m^3 or about 70% of the value at the inlet.
  - Arsenic increased to the second most abundant element at the outlet from the eighth rank at the inlet.
  - Copper and iron were reduced in relative abundance from first and second at the inlet to third and fourth, respectively, at the outlet.

TABLE 7. COMPARISON OF TOTAL ELEMENTAL CONCENTRATIONS AT THE ESP INLET AND OUTLET

Element	Concentration,[a] mg/m^3 Inlet	Outlet	Concentration ratio, outlet to inlet	Estimated ESP efficiency[b]
Ag	0.31	0.08	0.26	64
Al	41	0.78	0.02	97
As	18	7.9	0.44	38
Au	<0.002	<0.001	–[c]	–[c]
Ba	–[c]	<0.05	–[c]	–[c]
Cd	6.0	0.20	0.03	96
Co	0.15	<0.02	<0.13	>82
Cr	0.67	0.046	0.07	90
Cu	480	6.3	0.01	98
F	64	45	0.70	2
Fe	470	3.0	0.01	98
Hg	0.010	0.005	0.50	30
Mo	25	0.85	0.03	96
Ni	0.81	<0.10	<0.12	>83
Pb	20	0.47	0.02	97
Sb	2.5	0.16	0.06	92
Se	1.5	0.026	0.02	97
V	0.29	–[c]	–[c]	–[c]
Zn	26	1.9	0.07	90

a. Averages calculated from the data in Tables 5 and 6. Expressed for 21°C (70°F) and 760 mmHg.

b. Based on the data in the preceding column and an estimated 40% in-leakage of air (based on data in Table 11).

c. Not determined.

The observations about relative concentrations at the inlet and outlet of the ESP give a qualitative indication of the effect of the ESP in controlling emission rates of the various elements. A more nearly quantitative indication of the ESP efficiencies for controlling the various elements is given by the data in the last column of Table 7. These data are based on the ratios of the outlet and inlet concentrations and an estimated value of the in-leakage of air between the ESP inlet and outlet. The estimated value of the in-leakage of air is 40% of the reverberatory off-gases; this figure is based on analyses of flue gases at the ESP inlet and outlet, which are summarized later in Table 11. From the estimated ESP efficiencies for the individual elements, the following conclusions may be reached:

- Most of the elements were removed from the gas stream by efficiencies in excess of 90%.
- Three elements (arsenic, fluorine, and mercury) were exceptions to this rule, being removed by efficiencies less than 50%. A reasonable inference from this observation is that these three elements occurred to a large degree as vapors; this conclusion is supported by other data discussed in the paragraphs immediately following.
- A fourth element (silver) was another exception. There is no basis, however, for believing that this element occurred as a vapor to any marked degree.

Apparent Vapor-Phase Concentrations--

ESP inlet-- An analysis of the data obtained for the Institute's fractionated samples in the CFI train gives a basis for estimating the fraction of each element that occurred in the vapor phase at the ESP inlet. The data in question are given in the tables in Appendix C. The analysis of these data consisted of calculating the ratio of material collected outside the duct (on the filter and in the impingers) to the total amount of material collected.

The values of the ratios thus obtained are presented in Table 8. They permit the identification of the following elements as substances occurring to an appreciable degree in the vapor phase: arsenic (42 to 66%), fluorine (97 to 98%),

TABLE 8. FRACTIONS OF TOTAL ELEMENTAL CONCENTRATIONS APPEARING AS VAPORS AT THE ESP INLET

Date	Jan. 15			Jan. 16		
Sampling train	CFI			CFI		
	Concentration, mg/m³			Concentration, mg/m³		
Element	Total[a]	Vapor[b]	Vapor fraction	Total[a]	Vapor[b]	Vapor fraction
Ag	0.13	<0.02	<0.15	0.32	<0.02	<0.06
Al	26	0.22	<0.01	82	1.8	0.02
As	13	8.6	0.66	23	9.6	0.42
Au	<0.001	<0.001	–[c]	<0.001	<0.001	–[c]
Ba	0.070	<0.04	–[c]	0.38	<0.04	–[c]
Cd	1.2	<0.01	<0.01	9.4	<0.01	<0.01
Co	0.05	<0.03	–[c]	0.08	<0.03	–[c]
Cr	0.52	<0.02	<0.04	0.88	<0.02	<0.02
Cu	330	0.087	<0.01	960	0.14	<0.01
F	34	33	0.97	60	59	0.98
Fe	250	0.125	<0.01	840	0.21	<0.01
Hg	0.011	0.011	1.00	0.021	0.021	1.00
Mo	13	<0.06	<0.01	31	<0.06	<0.01
Ni	0.49	<0.02	<0.04	1.5	0.064	0.04
Pb	4.4	<0.03	<0.01	25	<0.03	<0.01
Sb	4.0	<0.04	<0.01	3.5	<0.03	<0.01
Se	1.0	0.081	0.08	3.0	0.20	0.07
V	0.07	<0.06	–[c]	0.17	<0.06	–[c]
Zn	23	0.084	<0.01	54	1.6	0.03

a. Based on data in Table 5 (originally compiled from data in Tables C-4 and C-5 in Appendix C). Calculated for 21°C (70°F) and 760 mmHg.

b. Compiled from data in Tables C-4 and C-5 in Appendix C. Also calculated for 21°C (70°F and 760 mmHg.

c. Not determined.

mercury (100%), and selenium (7 to 8%). Each of these elements except selenium was also found to be collected by the ESP with low efficiency (see Table 7). On the other hand, silver cannot be rated as a vaporous element despite its low collection efficiency in the ESP.

ESP outlet--In principle, the data obtained by the Institute at the ESP outlet could be treated in the same manner as the data for the inlet. In actuality, such a treatment would not be fruitful because of large relative uncertainties in the amounts of material collected in the impingers at the outlet. However, Radian collected a sample at the outlet under conditions designed to collect vapors selectively (by use of the vapor train described on page 20). The results of the analysis of this sample are given in Table 9. For comparison, the average values computed for the total elemental concentrations at the outlet (from Table 7) are also given in Table 9, along with the ratios of apparent vapor concentrations to total concentrations.

The information in Table 9 indicates that three elements found as vapors at the inlet—arsenic, fluorine, and mercury—occurred almost entirely as vapors at the outlet. This information also suggests that some of the other elements—aluminum, for example—occurred to a significant degree as vapors at the outlet. Such a conclusion does not seem plausible, however. Probably a better interpretation is that such elements occurred as fine particulates that were collected along with the vaporous elements.

Apparent Concentrations of Condensables--

An analysis of data for the Institute's samples from the CFI train permits not only an estimate of the fractions of the elements in the vapor phase, as discussed above, but an estimate of the fractions that condensed between the sampling duct and the external filter at 120°C. The results of the data analysis for the ESP inlet are given in Table 10. They show that for most of the elements, less than 1% appeared as condensable matter and that the maximum for any of the elements was 6% for arsenic in one of the two samples.

Discussion

This discussion of the trace-element data is addressed to two questions:

- What is the existing efficiency *versus* element of the ESP at the Hayden reverberatory furnace?
- Could the efficiency be significantly improved in theory if the option of operating the ESP at a lower gas temperature were exercised?

TABLE 9. TOTAL AND VAPOR CONCENTRATIONS OF ELEMENTS AT THE ESP OUTLET

Element	Concentrations,[a] mg/m³ Total[b]	Concentrations,[a] mg/m³ Vapor[c]	Ratio, vapor to total
Ag	0.08	0.015	0.17
Al	0.78	0.30	0.38
As	7.9	10	1.29[d]
Au	<0.001	<0.0001	–[e]
Ba	<0.05	<0.02	–[e]
Cd	0.20	0.00038	<0.01
Co	<0.02	<0.0002	–[e]
Cr	0.046	0.019	0.41
Cu	6.3	0.088	0.01
F	45	45	1.0
Fe	3.0	0.12	0.04
Hg	0.005	0.0044	0.88
Mo	0.85	0.0061	<0.01
Ni	<0.10	0.0028	–[e]
Pb	0.47	0.0044	0.01
Sb	0.16	0.0027	0.02
Se	0.026	0.00027	<0.01
V	–[e]	0.091	–[e]
Zn	1.9	0.0048	<0.01

a. At 21°C (70°F) and 760 mmHg.

b. From the third column of Table 7.

c. From the results of sampling by Radian with the vapor train.

d. The anomaly of this ratio stems from the comparison of data from different sources.

e. Not determined.

TABLE 10. FRACTIONS OF TOTAL ELEMENTAL CONCENTRATIONS APPEARING AS CONDENSABLE MATTER AT THE ESP INLET

Date	Jan. 15			Jan. 16		
Sampling train	CFI			CFI		
	Concentration, mg/m³		Condensable fraction	Concentration, mg/m³		Condensable fraction
Element	Total[a]	Condensables[b]		Total[a]	Condensables[b]	
Ag	0.13	<0.003	<0.02	0.32	<0.003	<0.01
Al	26	<0.03	<0.01	82	1.5	0.02
As	13	0.082	0.01	23	1.4	0.06
Au	<0.001	–[c]	–[c]	<0.001	–[c]	–[c]
Ba	0.070	–[c]	–[c]	0.38	–[c]	–[c]
Cd	1.2	<0.001	<0.01	9.4	<0.001	<0.01
Co	0.05	<0.001	<0.02	0.08	<0.001	<0.01
Cr	0.52	<0.001	<0.01	0.88	<0.002	<0.01
Cu	330	0.011	<0.01	960	0.015	<0.01
F	34	–[c]	–[c]	60	–[c]	–[c]
Fe	250	0.015	<0.01	840	0.046	<0.01
Hg	0.011	<0.001	<0.09	0.021	<0.001	<0.05
Mo	13	<0.005	<0.01	31	<0.005	<0.01
Ni	0.49	0.005	<0.01	1.5	0.064	0.04
Pb	4.4	<0.005	<0.01	25	<0.005	<0.01
Sb	1.0	<0.02	<0.02	3.5	<0.03	<0.01
Se	1.0	<0.01	<0.01	3.0	<0.01	<0.01
V	0.07	<0.001	<0.02	0.17	<0.001	<0.01
Zn	23	0.054	<0.01	54	1.6	0.03

a. Based on data in Table 5 (originally compiled from data in Tables C-4 and C-5 in Appendix C). Calculated for 21°C (70°F) and 760 mmHg.

b. Compiled from data in Tables C-4 and C-5 in Appendix C. Also calculated for 21°C (70°F) and 760 mmHg.

c. Not determined.

With respect to the first of these questions, the analytical data indicate that all elements except three identified as vaporous elements (arsenic, fluorine, and mercury) are collected with efficiencies exceeding 90% and that the elements accounting for most of the inlet mass (copper and iron) are collected with efficiencies around 98 to 99%. There may be some error in the quantitative aspects of these data owing to the uncertainty in the air in-leakage factor, but the conclusions are qualitatively correct.

With respect to the second question, it should be pointed out that the gas stream entering the ESP averaged around 260°C (500°F), whereas theoretically it might be cooled to a lower temperature—say 120°C (250°F). The comparison of quantities of condensed material and total material at the ESP inlet indicates that the condensables represented only a small fraction of the total elemental concentrations. Hence, it would appear that lowering the ESP temperature would not give a substantial increase in efficiency. On the other hand, a comparison of condensed material and total material at the ESP outlet might suggest that the absolute emission rate could be substantially reduced by cooling the gas stream to 120°C. Unfortunately, the poor accuracy of analytical data for the outlet precludes any test of this point. It must be emphasized that this discussion of condensables is based entirely on analyses of selected elements, not including sulfur, for example. The condensation of sulfur trioxide as sulfuric acid could increase the quantity of condensables significantly. Also, other considerations—such as loss of stack draft at a lower gas temperature—could weigh against any marked reduction in ESP temperature.

ANALYSIS OF OTHER MATERIALS IN THE REVERBERATORY OFF-GASES

Southern Research Institute was responsible for determining the concentrations of sulfur oxides, carbon dioxide, oxygen and water vapor in the reverberatory furnace off-gases. Methods used for this work are described in Appendix C. The results are given in Table 11. These data are mainly of interest in connection with the following points:

- Evidence of air in-leakage between the inlet and outlet of the ESP. The concentrations of carbon dioxide and water vapor were lower at the outlet than at the inlet, whereas the reverse was true for oxygen. These concentration differences are consistent with air in-leakage at a rate of about 40% of the stack gases.

- Levels of sulfur oxides. Most of the data for sulfur dioxide and sulfur trioxide are for the ESP outlet. Here, the averages of the concentrations observed are 0.53% (5300 ppm) for sulfur dioxide and 0.0028% (28 ppm) for sulfur trioxide. The relative concentration of

TABLE 11. CONCENTRATIONS OF MISCELLANEOUS GASES OBSERVED AT THE ESP INLET AND OUTLET

Gas	Location	Concentration, volume %, found on Jan. 12	Jan. 14	Jan. 15	Jan. 16
CO_2	Inlet	-	-	10.4	9.4
	Outlet	6.9 7.1	6.5 7.0 7.1 7.8	- -	- -
O_2	Inlet	-	-	5.2	7.3
	Outlet	9.6 7.7	9.5 9.5 8.7 8.2	- -	- -
H_2O	Inlet	-	-	9.3	9.7
	Outlet	7.5	7.8	-	-
SO_2	Inlet	-	-	0.83	-
	Outlet	0.62 0.56 0.36	0.52 0.57	- -	- -
SO_3	Inlet	-	-	0.0036	-
	Outlet	0.0033 0.0037 0.0022	0.0025 0.0026		

sulfur trioxide is surprisingly low in comparison with relative concentrations observed in coal-fired electric power plants.

ANALYSIS OF OTHER MATERIALS ASSOCIATED WITH THE REVERBERATORY FURNACE

Other materials analyzed besides those in the reverberatory off-gases were feed material for the reverberatory furnace and dust removed from the ESP hoppers. The data are given as part of the experimental record, but no interpretation or discussion of these data seems to be needed in connection with the primary analytical task of describing emissions from the reverberatory furnace and the electrostatic precipitator.

Feed Material

A sample of reverberatory feed material was prepared as a composite of individual samples collected on January 12, 14, 15, and 16 and submitted for analysis by spark-source mass spectrometry (SSMS) at Accu-Labs Research, Inc., of Wheat Ridge, Colorado. The results submitted by Accu-Labs are given in Table 12.

Hopper Dust

A sample of hopper dust was prepared as a composite of individual samples that were deposited in the ESP on January 12, 14, 15, and 16. Portions of the composite were submitted for analysis by Accu-Labs (SSMS), Radian (see Appendix B for methods), and the Institute (see Appendix C). The results obtained by the three organizations are compared in Table 13. The results of analyses of the individual samples of hopper dust, which were made by the Institute, are given in Table 14.

TABLE 12. RESULTS OF SSMS ANALYSIS OF REVERBERATORY FEED

Element	Concn, mg/g	Element	Concn, mg/g	Element	Concn, mg/g
*Ag	0.015	Hf	0.0028	Rh	<0.0001
*Al	>10	*Hg	Not reported	Ru	<0.0001
As	0.15	Ho	0.00035	S	>10
*Au	<0.0001	I	Int. Std	*Sb	0.048
B	0.0017	In	-	Sc	0.0048
*Ba	0.14	Ir	<0.0001	*Se	0.078
Be	<0.00024	K	>10	Si	>10
Bi	0.035	La	0.017	Sm	0.0017
Br	0.0034	Li	0.0029	Sn	0.210
Ca	2.4	Lu	0.00033	Sr	0.049
*Cd	0.014	Mg	>5	Ta	0.0019
Ce	0.020	Mn	0.17	Tb	0.00038
Cl	0.070	*Mo	0.60	Te	0.0033
*Co	0.39	Na	0.14	Th	0.0096
*Cr	0.047	Nb	0.0036	Ti	1.7
Cs	0.0011	Nd	0.013	Tl	0.0027
*Cu	>10	*Ni	0.083	Tm	0.00051
Dy	0.0012	Os	<0.0001	U	0.0058
Er	0.0023	P	0.40	*V	0.038
Eu	0.0012	*Pb	0.25	W	0.014
*F	0.54	Pd	<0.0001	Y	0.0076
*Fe	>10	Pr	0.0045	Yb	0.0016
Ga	0.00087	Pt	<0.0001	Zr	0.085
Gd	0.00096	Re	Int. Std	*Zn	0.60
Ge	0.0033	Rb	0.016		

* These elements were determined analytically in the reverberatory off-gases.

TABLE 13. RESULTS OF SSMS ANALYSIS OF A COMPOSITE OF HOPPER-DUST SAMPLES

Element	Concentration, mg/g Accu-Labs	Concentration, mg/g Radian	Concentration, mg/g SRI	Element	Concentration, mg/g Accu-Labs	Concentration, mg/g Radian	Concentration, mg/g SRI
Ag	0.082	0.095	0.090	Mo	>10	11	8.2
Al	>10	12.5	19.3	Na	1.4		
As	4.1	2.7	3.6	Nb	0.0036		
Au	0.00025	<0.0001	<0.0005	Nd	0.050		
B	0.0017			Ni	0.055	0.18	0.17
Ba	0.180	0.0035	0.61	Os	<0.0001		
Be	0.0016			P	2.4		
Bi	5			Pb	>10	8.3	6.6
Br	0.060			Pd	<0.0001		
Ca	>5			Pr	0.014		
Cd	2.0	3.1	2.0	Pt	<0.0001		
Ce	0.053			Re	Int. Std.		
Cl	0.049			Rb	0.061		
Co	0.39	0.53	0.27	Rh	<0.0001		
Cr	0.37	0.24	0.30	Ru	<0.0001		
Cs	0.011			S	>10		
Cu	>10	217	246	Sb	1.7	0.93	1.6
Dy	0.0032			Sc	0.0027		
Er	0.0035			Se	0.93	0.25	0.96
Eu	0.0013			Si	>10		
F	1.2	0.39	0.44	Sm	0.0083		
Fe	>10	300	197	Sn	>10		
Ga	0.0065			Sr	0.057		
Gd	0.048			Ta	0.00087		
Ge	0.16			Tb	0.00081		
Hf	0.0055			Te	0.033		
Hg	Not reported	0.00055	0.001	Th	0.0064		
Ho	0.0010			Ti	>10		
I	0.330			Tl	0.0094		
In	Int. Std.			Tm	0.00077		
Ir	<0.0001			U	0.0058		
K	>10			V	0.070	0.098	0.047
La	0.060			W	0.12		
Li	0.014			Y	0.026		
Lu	0.00050			Yb	0.0028		
Mg	>5			Zr	0.11		
Mn	0.64			Zn	>10	12	16

TABLE 14. RESULTS OF CHEMICAL ANALYSES OF INDIVIDUAL HOPPER SAMPLES

	Concentration, mg/g, on			
Element	Jan. 12	Jan. 14	Jan. 15	Jan. 16
Ag	0.080	0.090	0.060	0.080
Al	18.5	17.8	19.7	19.0
As	4.8	5.0	2.4	3.5
Au	<0.0005	<0.0005	<0.0005	<0.0005
Ba	0.67	0.56	0.64	0.57
Cd	2.9	3.0	1.3	2.5
Co	0.22	0.23	0.29	0.26
Cr	0.28	0.29	0.29	0.32
Cu	245	237	243	243
F	0.50	0.43	0.42	0.55
Fe	179	192	185	213
Hg	<0.001	<0.001	<0.001	<0.001
Mo	9.4	9.2	7.1	9.1
Ni	0.22	0.22	0.22	0.16
Pb	6.8	9.4	5.2	7.8
Sb	1.7	1.7	1.1	1.3
Se	0.62	0.72	1.1	0.64
V	0.042	0.046	0.050	0.042
Zn	20	19	13	18

SECTION 6

PARTICLE SIZE DISTRIBUTION MEASUREMENTS

Inertial, optical and electrical mobility methods were used to measure particle size distributions from 0.01 μm to 8.0 μm diameter. Measurements were made at the inlet and outlet of the electrostatic precipitator in vertical sampling ports. Both at the inlet and outlet, hoppers were located directly beneath the sampling points, and at both sampling locations, the ductwork was approximately 20 feet deep. Because of flow disturbances caused by the hoppers, it was not feasible to obtain a representative sample for particle diameters greater than about 5.0 μm. Therefore, no traverses were made.

Cascade impactors were used for in situ sampling at the inlet and outlet. At the inlet, modified Brink BMS-11 impactors were used, and at the outlet, measurements were made with University of Washington Mark III Source Test Cascade Impactors (U of W). These two impactors are shown in Figures 4 and 5. The collection stages of these impactors are usually too massive to be accomodated in any type of field-portable balance sensitive enough to detect weighing differences of 0.01 mg. Therefore, light weight inserts were fabricated for these collection stages. Glass-fiber filter mats as well as properly formed metal shimstock can be used. During preliminary tests conducted in December, 1976, particulate matter samples obtained with cascade impactors at the inlet and outlet were found to adhere well to bare metal impaction surfaces. Therefore, during the test in January lightweight metal collection stage inserts were used in both inlet and outlet impactors. These inserts were fabricated from 300 series stainless steel shimstock and were cleaned prior to use in an ultrasonic cleaner with benzene, acetone, and distilled water. Next, the inserts or "substrates" were baked at 343°C (650°F) for one hour. After initial weighings the substrates were dessicated until use. After use, the substrates were dessicated for a minimum of 12 hours before final weighing. Back-up filters used in the Brink and U of W impactors were acid washed, in situ conditioned Reeve Angel 934 AH glass-fiber filter material. These substrates were prepared according to the procedures given in E.P.A. report 600/7-77-060. After in situ conditioning, the back-up filters were dessicated at least 12 hours before initial weighings were made. After use, the glass-fiber filter material was again dessicated for at least 12 hours

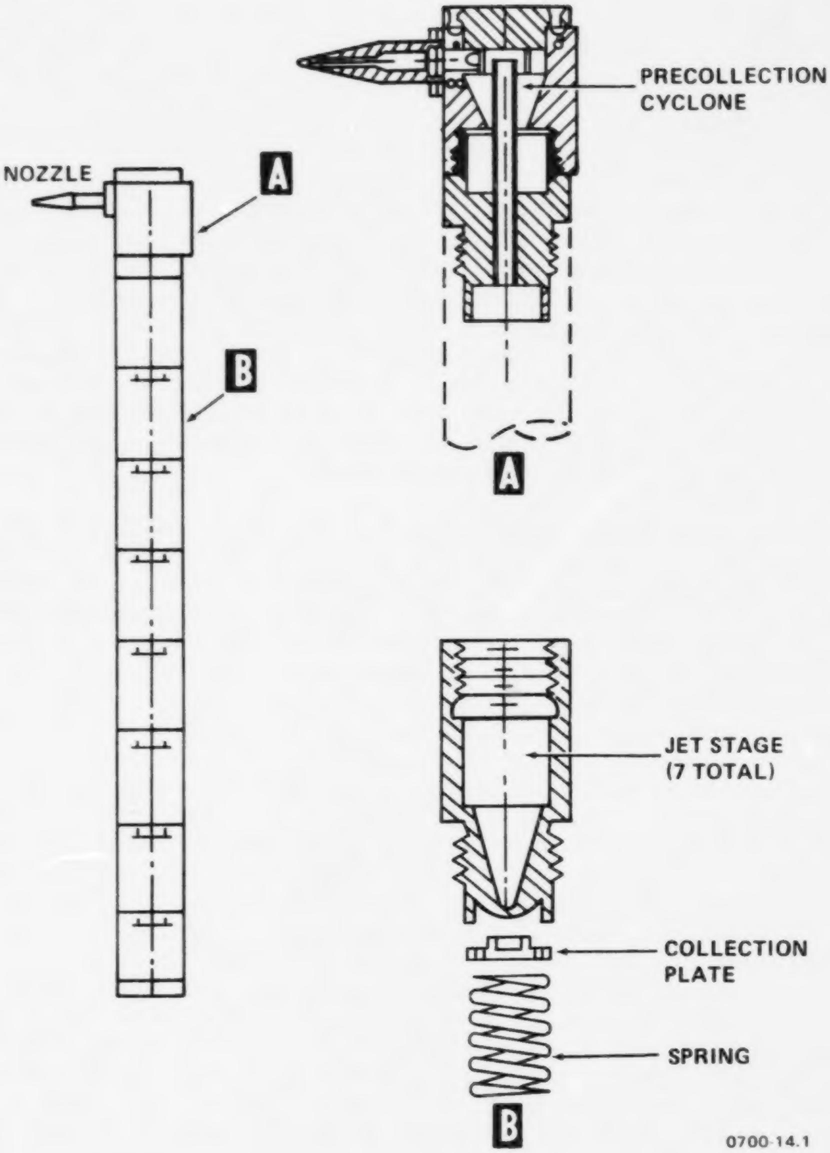

Figure 4. Modified Brink BMS-11 cascade impactor used for inlet particle size distribution measurements.

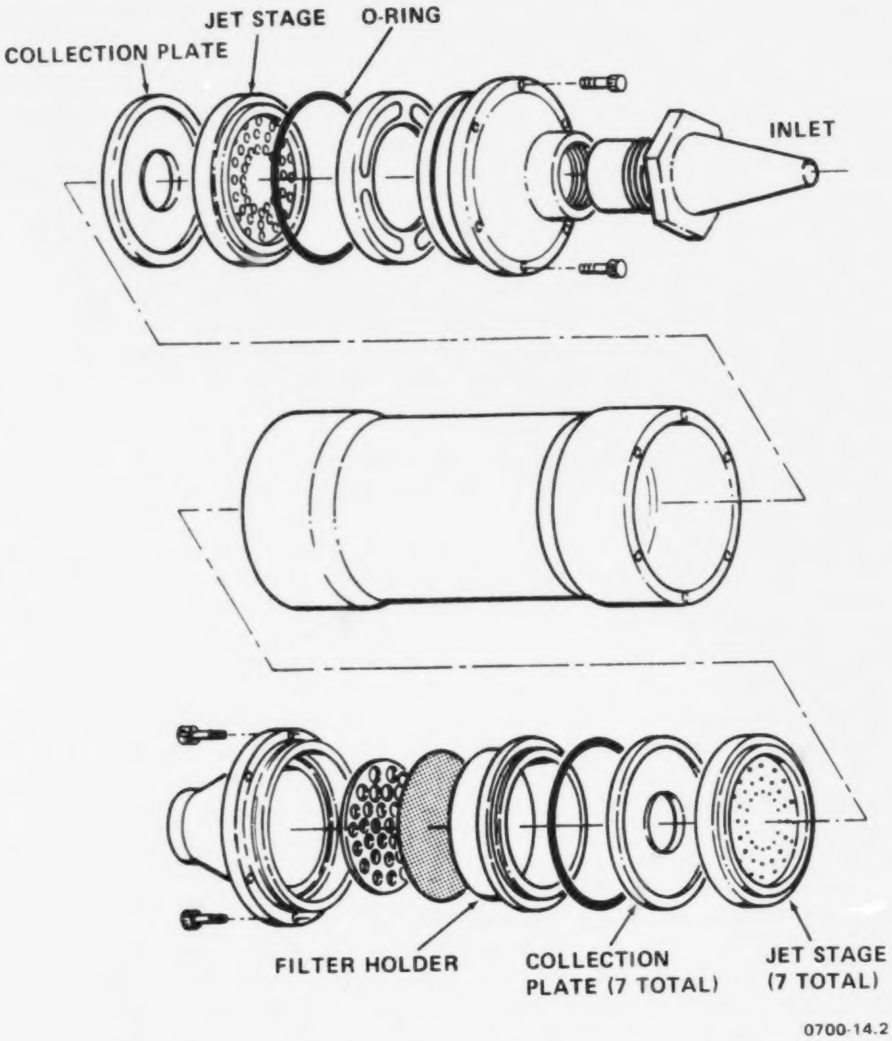

Figure 5. University of Washington Mark III Source Test Cascade Impactor used for outlet particle size distribution measurements.

before final weighings were made. All inlet impactor substrates and back-up filters were weighed on a Cahn model G-2 electrobalance. All outlet impactor substrates and back-up filters were weighed on a Cahn model 4100 electrobalance equipped with a specially designed "weigh-below" chamber, built to accomodate the 75 mm diameter U of W impactor substrates. The weighing precision with these balances as used under field conditions is approximately ± 0.05 mg.

Since the particulate matter was cohesive, no particle "bounce" problems were encountered. If the particles are not cohesive and do not adhere well to the collection substrates, it is possible for large particles to be re-entrained or "bounce" from one stage to another, finally being caught by the back-up filter. In such an instance, the back-up filter catch is not comprised of particles whose diameter is generally smaller than the D_{50} of the last impactor stage, and the filter catch is meaningless for data reduction purposes. Here the back-up filter catch masses are meaningful and these were included in the calibrations for cumulative mass.

During each day of sampling, one impactor at each sampling location was run as a "blank". The impactor was prepared as if a normal sample were to be taken, but a filter was placed in front of the impactor so that only clean flue gas could enter and pass through. The impactor was placed in the duct, allowed to warm up, and an impactor "run" was made at a flowrate and run time commensurate with those of the other impactor runs made at the same sampling location on that day. Afterwards, the substrates were weighed and compared with their initial weights. In this manner, background measurements were made to allow for the effect of the flue gases on the impactor substrates and back-up filters on a daily basis. Tables 15 and 16 show the results of these blank impactor runs made at the inlet and outlet of the precipitator. Averages were calculated each day to find a correction which would be applied to the stage weights for that day. Only one back-up filter blank was obtained at each sampling location daily as opposed to several blanks for the impactor stages. This single value was judged to be too uncertain for use as a correction so a pooled correction value based on all back-up filter blanks was used rather than daily averages as were used for two stages. Also, since the first collection stage of the U of W impactor (S1) is different in design from that of the following collection stages (S2-S7), the four S1 blank substrate weight changes were averaged to obtain a pooled correction for S1 which was used for all outlet runs.

Helium pycnometer density measurements made on ash collected at the inlet indicated a density of 3.13 gm/cm^3. At the outlet, the density was measured to be 1.84 gm/cm^3. This creates some difficulty in interpreting the impactor data because the characteristic stage cutoff diameters of the impactors are density

TABLE 15.

INLET MODIFIED BRINK IMPACTOR BLANK STAGE MASS GAINS

Date	1-2-77	1-14-77	1-15-77	1-16-77
Substrate Set #	3N	6N	9N	13N
Sample Time (min)	30	30	30	30
Temperature (°C)	243	232	246	243
Cyclone (mg)	NA	NA	NA	NA
SO (mg)	0.08	0.38	0.18	0.24
S1 (mg)	-0.04	0.38	0.28	0.28
S2 (mg)	0.36	0.32	0.11	0.46
S3 (mg)	0.12	0.44	0.02	0.36
S4 (mg)	0.00	0.40	0.18	0.16
S5 (mg)	-0.08	0.36	0.06	0.24
SF (mg)	-4.04*	0.28	0.24	0.28
SO-S5 avg. (mg)	0.07±0.16	0.38±0.04	0.15±0.09	0.29±0.11
SF avg.	0.27±0.02			

*Excluded from SF average

TABLE 16.

OUTLET UNIVERSITY OF WASHINGTON IMPACTOR BLANK MASS GAINS

Date	1-12-77	1-14-77	1-15-77	1-16-77
Substrate Set #	96	93	88	86
Sample Time (min)	120	135	120	120
Temperature (°C)	177	168	185	174
S1 (mg)	1.18	-0.03	-0.07	1.90
S2 (mg)	0.28	0.32	0.23	1.41
S3 (mg)	0.33	0.25	0.25	1.82
S4 (mg)	0.39	0.21	0.20	1.01
S5 (mg)	0.29	0.32	0.24	0.75
S6 (mg)	0.31	0.22	0.21	0.55
S7 (mg)	0.38	0.30	0.34	0.79
SF (mg)	-1.28	-1.48	-0.94	-1.53
S2-S7 avg. (mg)	0.33±0.05	0.27±0.05	0.25±0.05	1.06±0.48

S1 avg. = 0.36±0.74

SF avg. = -1.31±0.27

dependent. It was concluded that the outlet density was the appropriate density to use for the fine particles as the outlet aerosol was comprised predominantly of these fine particles. The inlet density was assumed to be more representative of large particles, these large particles dominate the inlet aerosol on a total mass basis and are much more effectively collected by the ESP than the fine particle fraction of the inlet aerosol. Because the interest in this program centered on the ESP collection characteristics of the more difficult to remove, fine particle fraction of the aerosol, the particle density obtained from the outlet sample was used in making the cut size calculations for the impactors. This procedure will introduce errors in the fractional efficiencies for the large (say >5 μ diameter) particles but probably represents the best method for treating the data on fine particle emissions. (The tacit assumption is made that a particle does not change in size or density in passing through the ESP). The magnitude of the size shift resulting from the density assumption can be seen in a later discussion of the ultra fine particulate data. Any particle formation or growth as a result of cooling of volatile components of the gas stream is also ignored in the analysis of these data.

The particle size distributions described in this portion of the report are impactor measurements which have undergone treatments by a complex computer data reduction procedure. The computer programs involved were developed by Southern Research Institute under E.P.A. Contract 68-02-2131*. This set of computer programs performs fits to cumulative mass distribution data from each impactor run. Then differential size distributions, which provide measures of concentrations within small size intervals, are derived by differentiation of the fitted cumulative distribution curves. A set of statistical programs averages groups of these data, determines confidence intervals, and plots the results on a computer controlled plotting system.

In Appendix D, computer generated data sheets are reproduced. These data sheets give the corrected stage weights, run conditions, stage by stage cumulative masses, and differential size distributions calculated from the data for each inlet and outlet impactor run.

At the inlet the Brink impactors were used to obtain single point samples in port 2. Flowrates were chosen so that nozzle inlet velocities were isokinetic at the average flue gas velocity. The sampling point was 6 feet deep into a 20-foot flue with a 14-foot deep hopper underneath the duct. Inlet blank runs were usually run in the mornings in ports 1 or 3.

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* "A Data Reduction System for Cascade Impactors", McCain, Clinard, Felix, and Johnson, EPA-600/7-78-132a, July, 1978.

The inlet "real" runs were usually made in the afternoon because other equipment was using all of the available impactor ports in the mornings. A total of three "real" runs were made each day along with the one blank run described above. Typical inlet sampling times were about 30 minutes.

The inlet impactor runs show a slight trend toward increasing cumulative mass loading below 8μm diameter, with calendar progession. Differences in the differential distribution curves are slight, and there was no statistically significant difference in these curves for the first three days of testing. However, for 1/16/77 there does appear to be a significant, but small, increase in emissions in the 1.0-2.0μm size range. The day to day variations were small and, within the scatter of the data, not significant. Therefore, for the purposes of penetration-efficiency calculations, all the inlet runs were pooled and averaged. Figure 6 shows the averaged cumulative mass curve obtained from this average. As for all the particle size distribution curves presented in this report, 50% confidence intervals (probable error of the mean) are shown. Figure 7 shows the differential size distribution for the pooled inlet data. All particle diameters are based on an ash density of 1.84 gm/cm^3, and are Stokes' diameters. Examination of the dM/dlogD curve, Figure 7, shows a minimum in the mass emissions occurring near 1.0μm with another decrease indicated for particle diameters less than 0.25μm. The calculated inlet mass loadings for each impactor run are shown in Table 17. Note that these mass loadings cannot be compared with other data since the larger particle sizes (>5.0μm) could not be representatively sampled by the impactors because of isokinetic sampling limitations and inability to obtain complete traverses of the duct. For presentation purposes data plotting was cut off at 10μm; however, the data are probably not accurate above 5μm. A significant portion of the particulate was contained in particles larger than 10μm. Thirty (30) to sixty (60) percent of the inlet particulate was included in particles larger than 8μm even near the top of the run of deep, low velocity ducting.

At the outlet, U of W impactors were used to obtain single point samples in ports 4 and 5. Impactor flow rates were chosen to be isokinetic at the average duct velocity at the sampling location. The sampling points were 10 feet down in a 23-foot deep duct, with a 20-foot deep hopper underneath the duct. A total of three real runs was made each day along with the one blank run described previously. The average sampling time was 120 minutes.

The outlet size distributions show poor agreement on a day by day basis. These differences are most likely tied to the operation of the ESP, especially the electrical conditions observed in the ESP TR sets. These differences make it unreasonable to average the impactor runs over the four days of testing

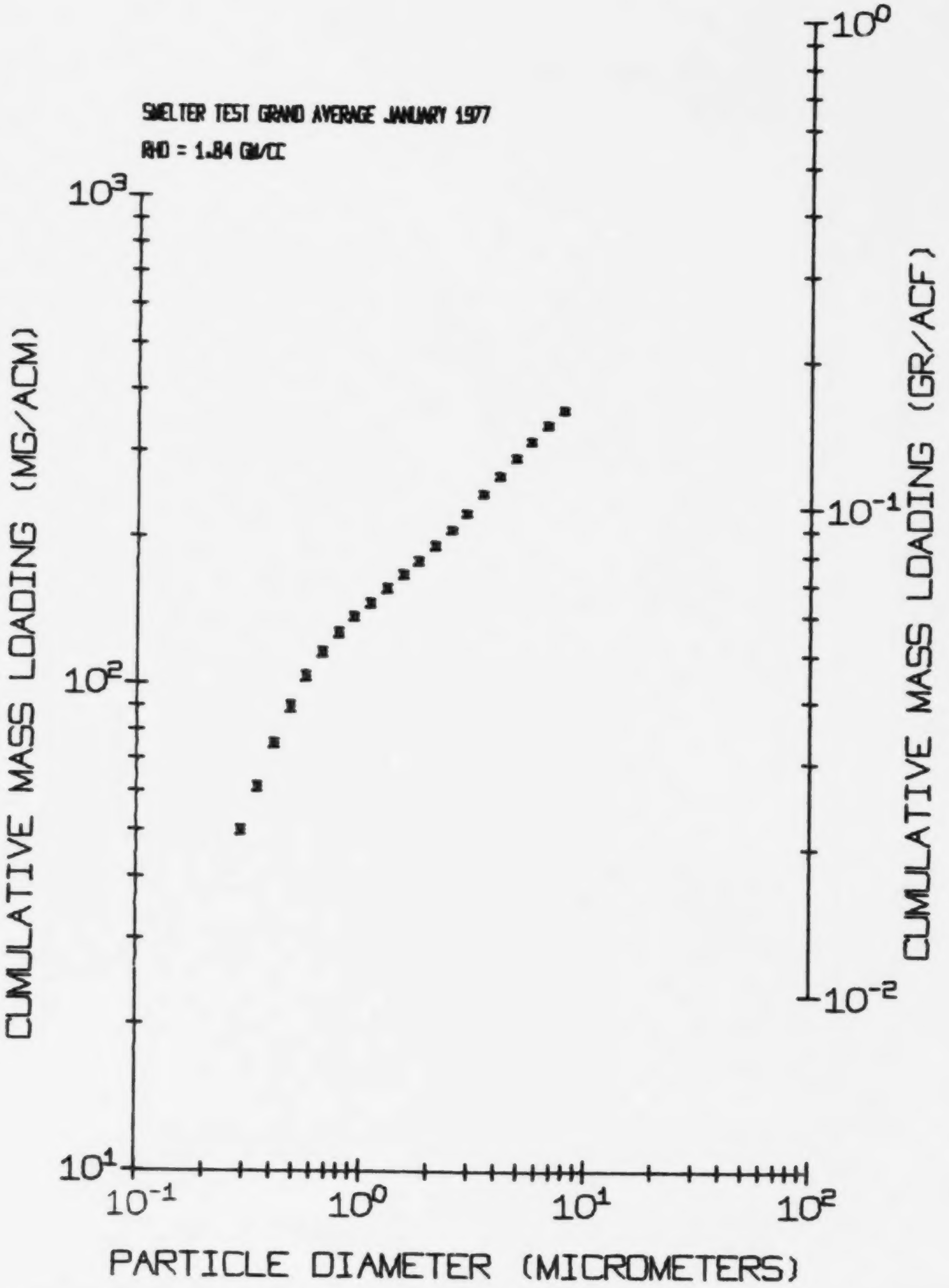

Figure 6. Inlet cumulative mass loading, averaged over all inlet impactor runs versus Stokes particle diameter. 50% confidence intervals are shown.

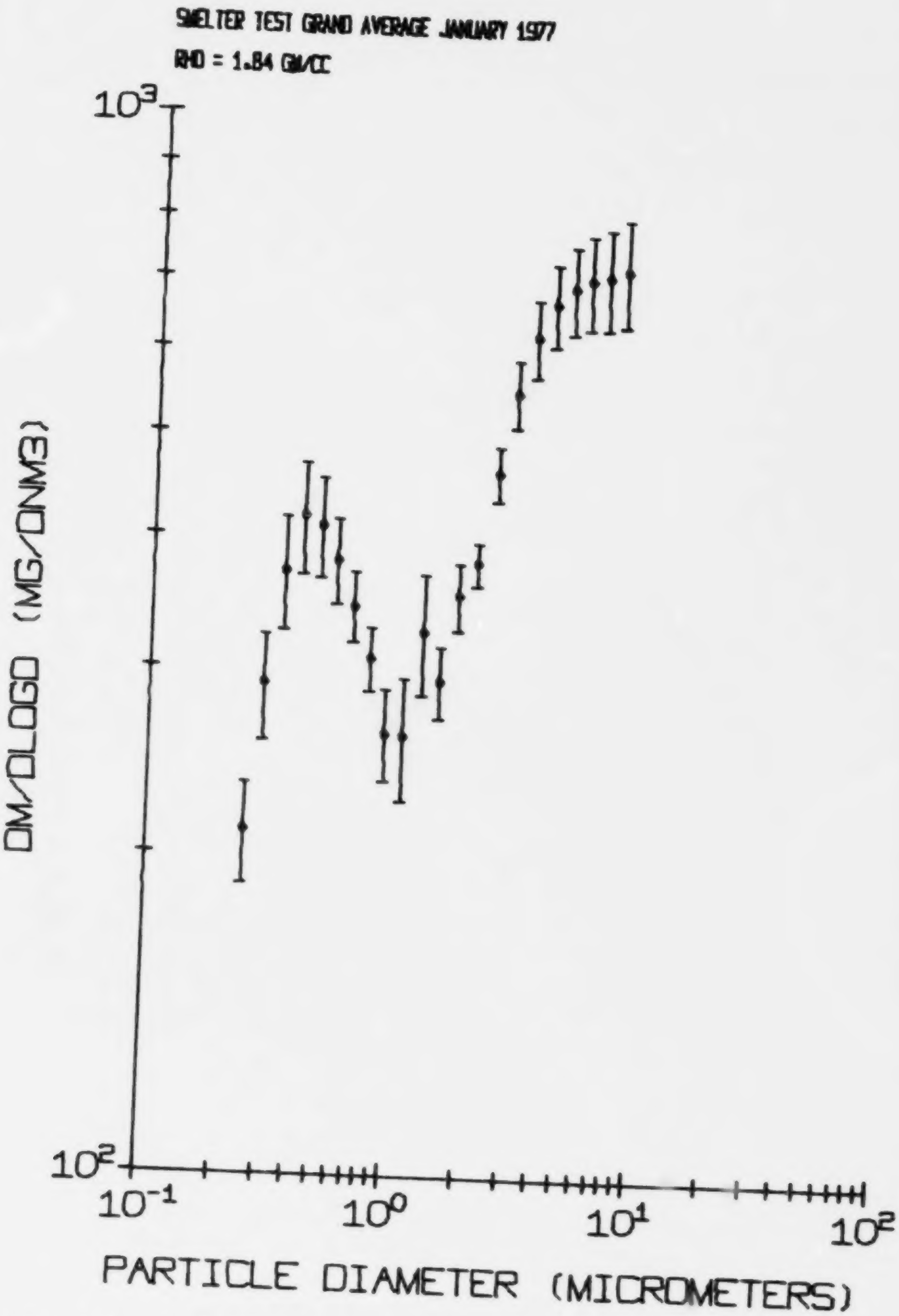

Figure 7. Inlet differential mass concentration (dM/dlogD), averaged over all inlet impactor runs versus Stokes particle diameter. 50% confidence intervals are shown.

TABLE 17.

CALCULATED IMPACTOR MASS LOADINGS FOR THE INLET SAMPLING LOCATION. NUMBERS IN PARENTHESES REFER TO THE POWER OF 10 MULTIPLIER

Run Code	Date	Time	Port No.	Grains/ACF	Grains/DNCF*	mg/ACM	mg/DNCM*
KCCI-1	1/12/77	1257	2	2.0202(-1)	4.0639(-1)	4.6229(2)	9.2996(2)
KCCI-3	1/12/77	1423	2	2.5793(-1)	5.1887(-1)	5.9024(2)	1.1873(3)
KCCI-4	1/12/77	1500	2	1.5953(-1)	3.2092(-1)	3.6506(2)	7.3436(2)
KCCI-5	1/14/77	1005	2	1.6866(-1)	3.4039(-1)	3.8595(2)	7.7893(2)
KCCI-7	1/14/77	1252	2	3.6300(-1)	7.1684(-1)	8.3067(2)	1.6404(3)
KCCI-8	1/14/77	1409	2	1.6031(-1)	3.1647(-1)	3.6685(2)	7.2419(2)
KCCI-10	1/15/77	1315	2	3.1218(-1)	6.2645(-1)	7.1438(2)	1.4335(3)
KCCI-11	1/15/77	1357	2	4.4437(-1)	9.1754(-1)	1.0169(3)	2.0996(3)
KCCI-12	1/15/77	1448	2	1.4994(-1)	3.0960(-1)	3.4312(2)	7.0848(2)
KCCI-14	1/16/77	1255	2	4.6350(-1)	9.6129(-1)	1.0606(3)	2.1997(3)
KCCI-15	1/16/77	1341	2	2.9486(-1)	6.0825(-1)	6.7473(2)	1.3919(3)
KCCI-16	1/16/77	1440	2	5.5007(-1)	1.1347(0)	1.2588(3)	2.5967(3)

*Normal, or Engineering Standard conditions are defined to be 21°C (70°F) and 760 mm (29.92in) Hg atmospheric pressure.

so individual averages were made for each day. Figures 8-15 show the cumulative and differential distribution curves for each day of testing on a Stokes diameter basis (based on a density of 1.84 gm/cm^3). Qualitatively, the curves show similar behavior for particulate emissions as a function of particle diameter. Data from January 12, 14 and 15 all show that the emissions increase with increasing particle diameter in the 0.5 to 0.8μm size range, reaching a maximum near 0.8μm and then decreasing to a minimum near 2μm. Similar behavior also is seen in the results of January 16 except that the sizes at which the maximum and minimum occur are shifted toward slightly smaller values. A similar behavior was observed in the inlet distributions except the maximum in that case was located at about 0.5μm and the minimum near 1μm. Particle growth by sublimation or condensation could result in this difference in the inlet and outlet behavior. The calculated outlet mass loadings for each impactor run are shown in Table 18. Again, these values are probably not representative of the entire duct since vertical concentration stratification was likely to have been severe for large particles.

Penetration-efficiency estimates were derived from the impactor data using the grand average for the inlet and daily averages for the outlet. Figures 16 through 19 show these penetration-efficiency curves. Fifty percent confidence intervals (probable errors) are shown about each efficiency point. The structure of these curves differs from day to day. Since the inlet particle size distribution appeared to be fairly stable from day to day, these differences are presumed to result from the daily variation in the behavior of the precipitator.

Inlet and outlet ultrafine particle size distribution measurements were made with both electrical mobility and optical methods. Two types of mobility analyses were considered for this test: (1) diffusional methods and (2) electrical mobility methods. Because of its compactness and short measurement time (29.5 kg and 2 minutes) as compared with the diffusional method (136 kg and 2 hours), the electrical mobility method was selected for use on this test. The instrument used was a Thermosystems model 3030 Electrical Aerosol Analyzer*. The electrical mobility method operates by placing a known charge on the particles and precipitating these particles under precisely controlled conditions. Size selectivity is obtained by varying the electric field in the precipitator section of the mobility analyzer. Charged particle mobility is monotonically related to particle

* Liu, B.Y.H., K. T. Whitby, and D.Y.H. Pui. "A Portable Electrical Aerosol Analyzer for Size Distribution Measurements of Submicron Aerosols". Presented at the 66th Annual Meeting of the Air Pollution Control Association, Paper No. 73-383, June, 1973.

TABLE 18.

CALCULATED IMPACTOR MASS LOADINGS FOR THE OUTLET SAMPLING LOCATION. NUMBERS IN PARENTHESES REFER TO THE POWER OF 10 MULTIPLIER

Run Code	Date	Time	Port No.	Grains/ACF	Grains/DNCF*	mg/ACM	mg/DNCM*
KCCO-1	1/12/77	1015	5	9.6698(-3)	1.6627(-2)	2.2128(1)	3.8048(1)
KCCO-2	1/12/77	1015	4	5.5090(-3)	9.4724(-3)	1.2606(1)	2.1676(1)
KCCO-3	1/12/77	1435	5	6.6411(-3)	1.1635(02)	1.5197(1)	2.6624(1)
KCCO-6	1/14/77	1016	4	9.4741(-3)	1.6302)-2)	2.1680(1)	3.7305(1)
KCCO-7	1/14/77	1145	5	8.3099(-3)	1.4659(-2)	1.9016(1)	3.3545(1)
KCCO-8	1/14/77	1145	4	6.3370(-3)	1.1179(-2)	1.4501(1)	2.5581(1)
KCCO-9	1/15/77	1000	4	1.0477(-2)	1.8425(-2)	2.3976(1)	4.2164(1)
KCCO-10	1/15/77	1000	5	1.3739(-2)	2.4161(-2)	3.1439(1)	5.5289(1)
KCCO-11	1/15/77	1410	4	1.2456(-2)	2.2450(-2)	2.8504(1)	5.1374(1)
KCCO-13	1/16/77	0915	4	1.5550(-2)	2.7467(-2)	3.5583(1)	6.2854(1)
KCCO-15	1/16/77	1345	4	4.2665(-3)	7.5832(-3)	9.7633(0)	1.7353(1)
KCCO-16	1/16/77	1345	5	5.1644(-3)	9.1791(-3)	1.1818(1)	2.1005(1)

*Normal, or Engineering Standard conditions are defined to be 21°C (70°F) and 760 mm (29.92 in) Hg atmospheric pressure.

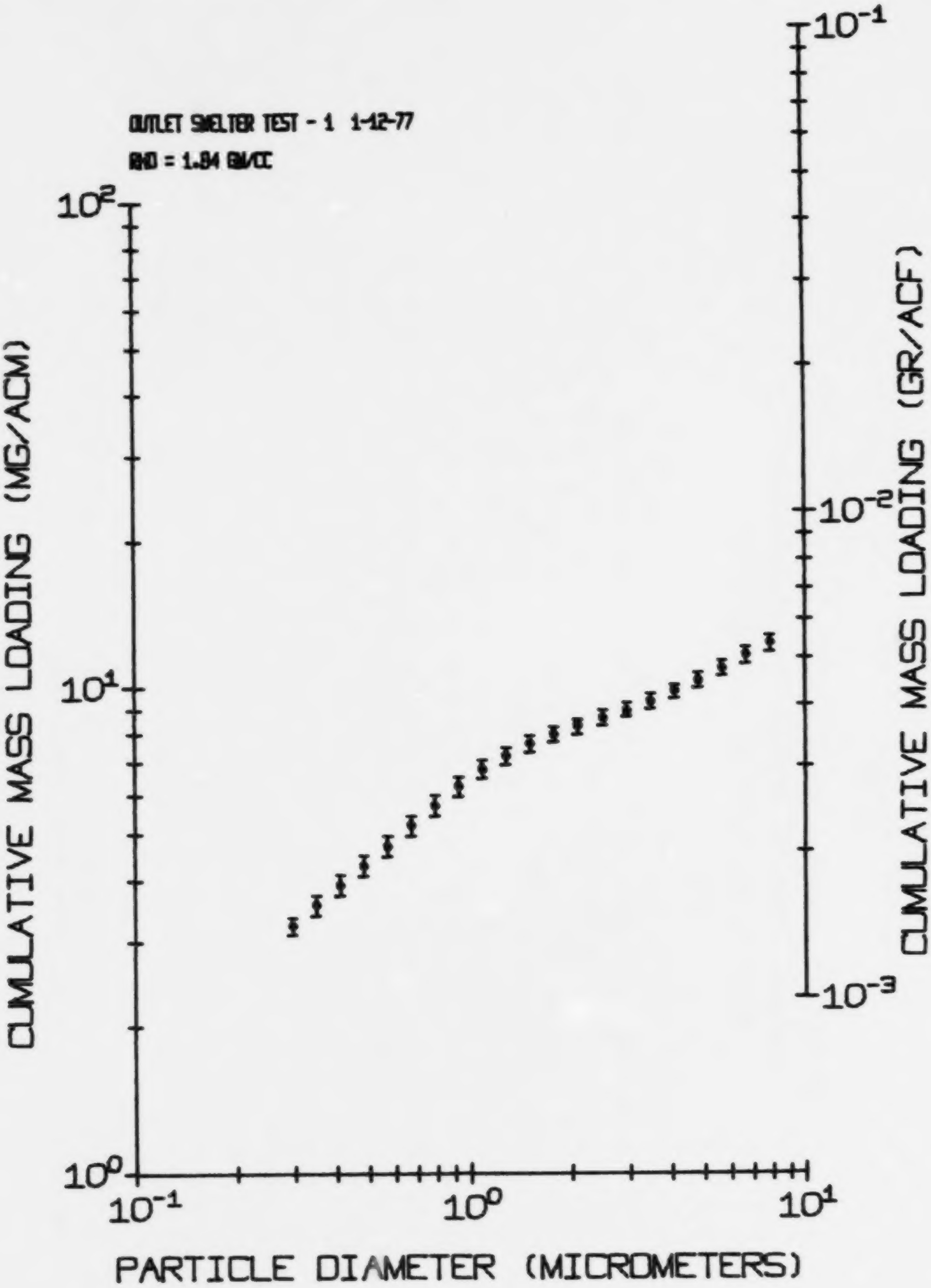

Figure 8. Outlet cumulative mass loading, averaged over the first day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

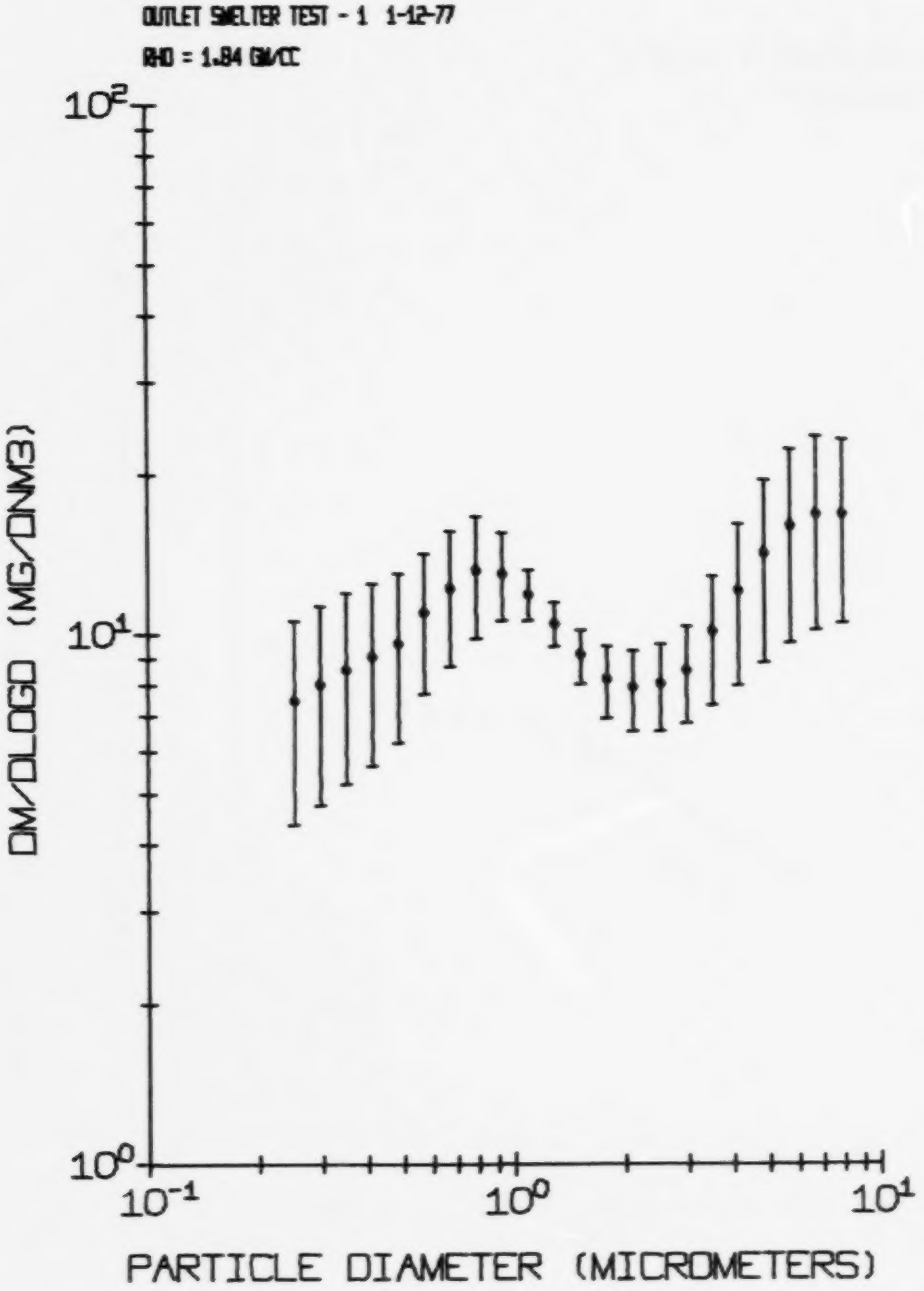

Figure 9. Outlet differential mass concentration (dM/dlogD), averaged over the first day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

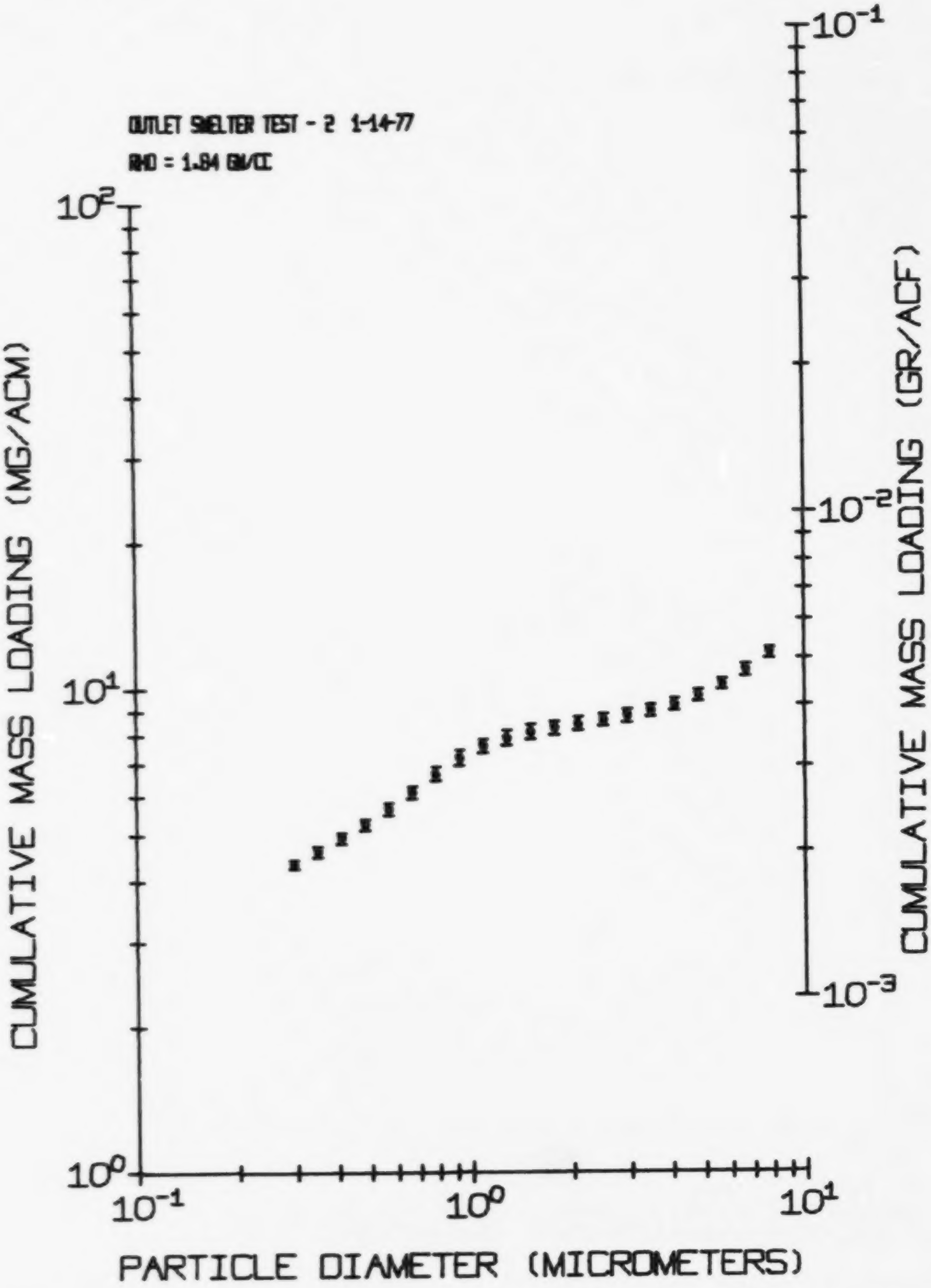

Figure 10. Outlet cumulative mass loading, averaged over the second day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

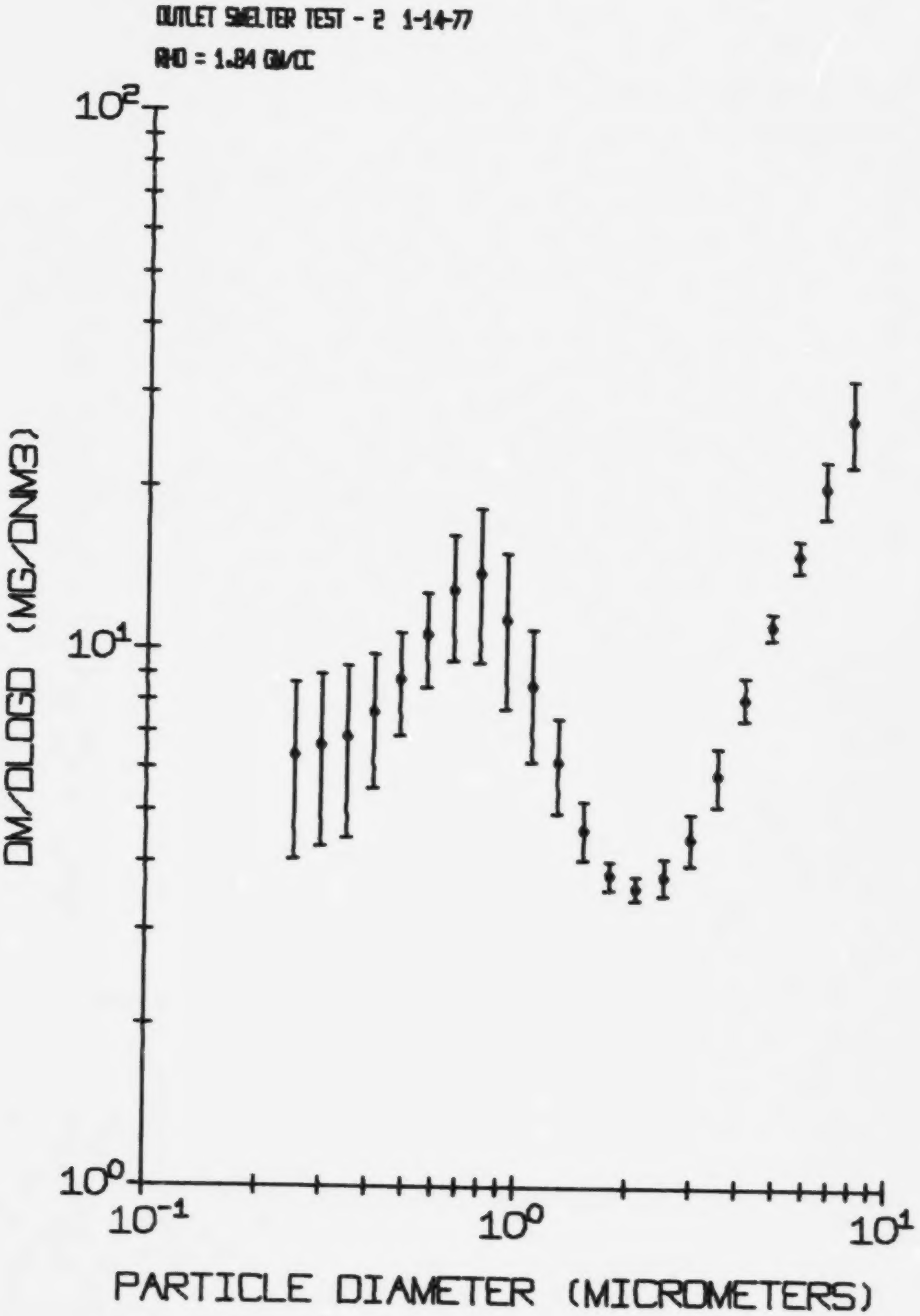

Figure 11. Outlet differential mass concentration (dM/dlogD), averaged over the second day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

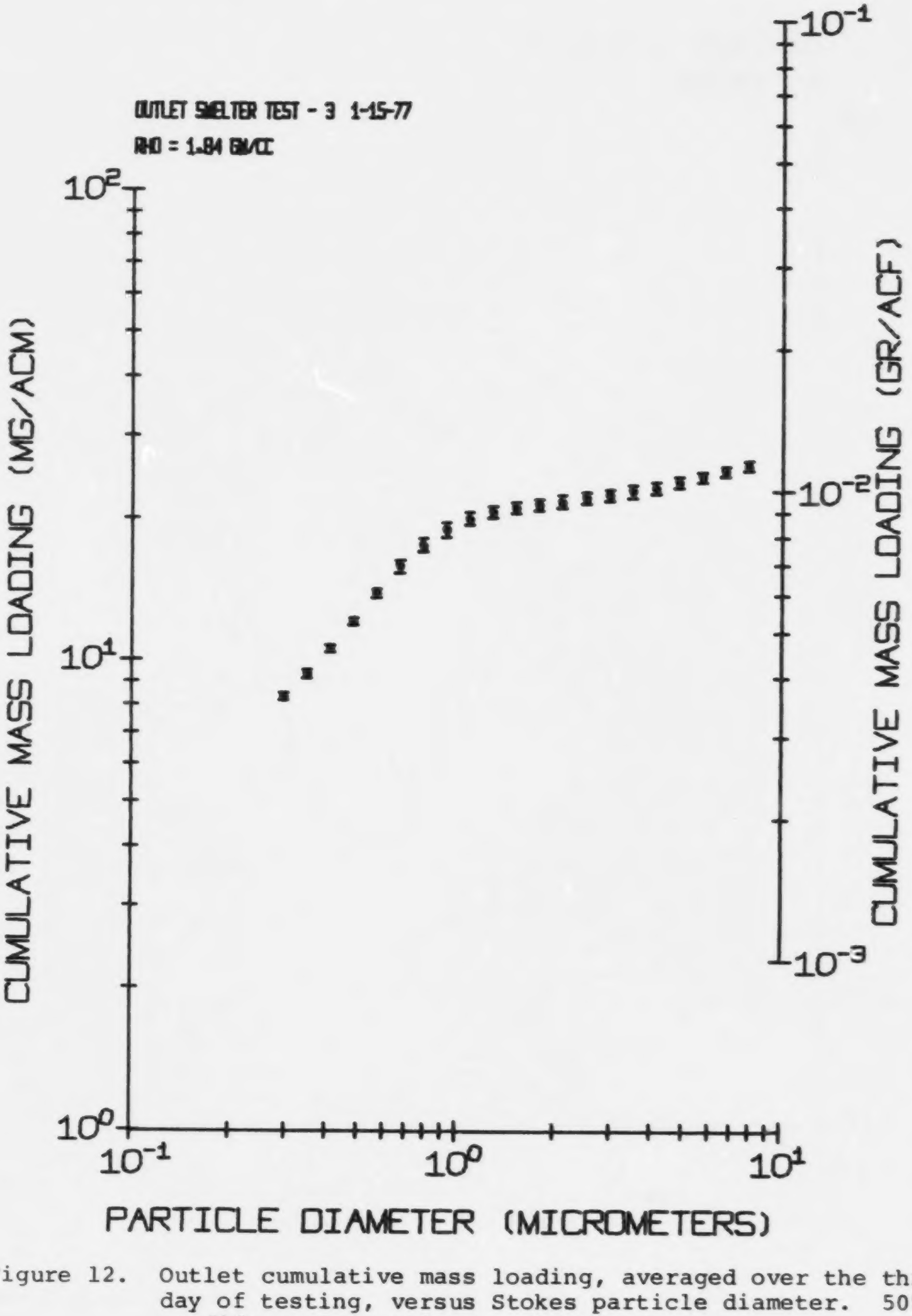

Figure 12. Outlet cumulative mass loading, averaged over the third day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

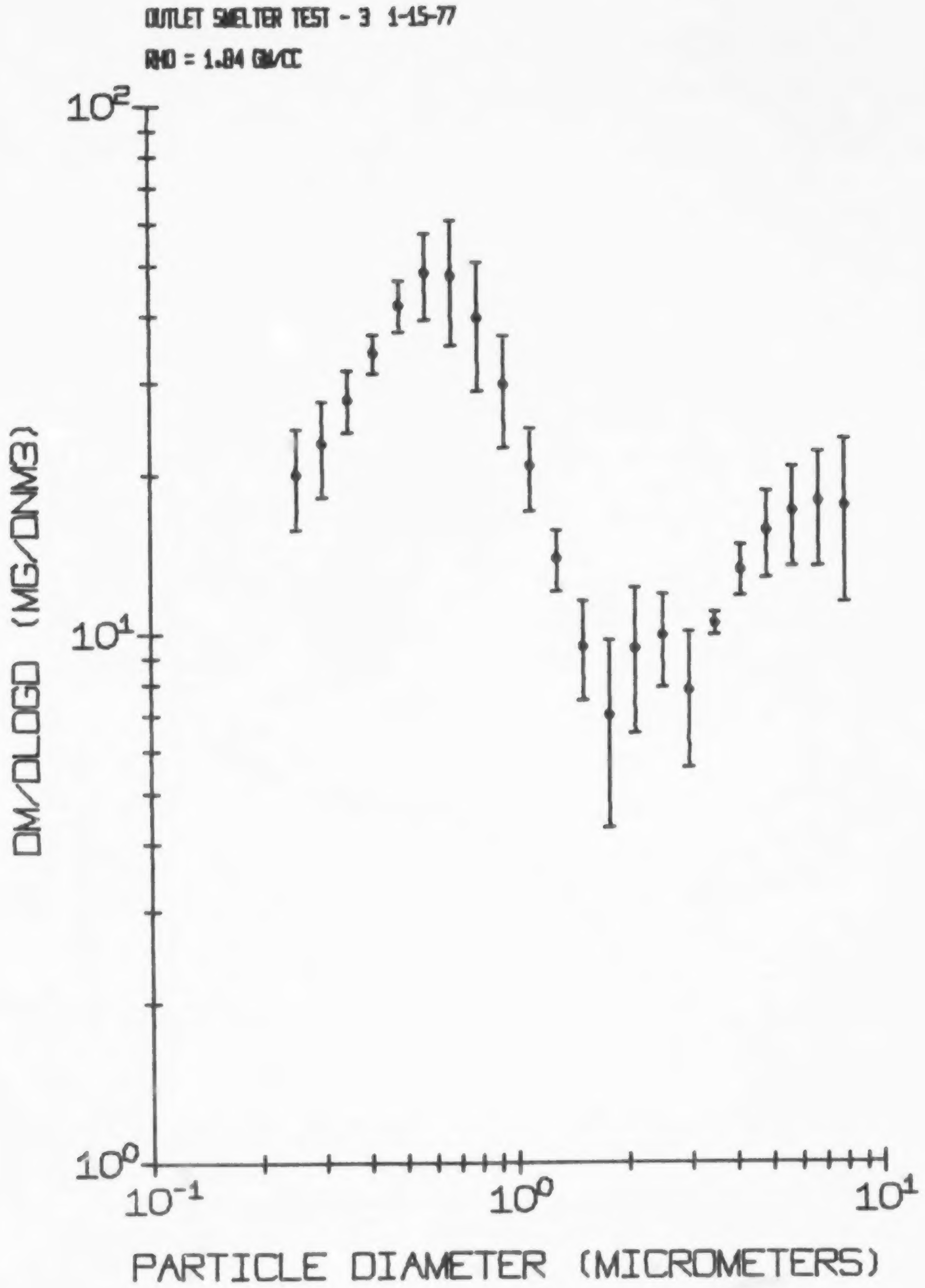

Figure 13. Outlet differential mass concentration (dM/dlogD), averaged over the third day of testing, versus Stokes diameter. 50% confidence intervals are shown.

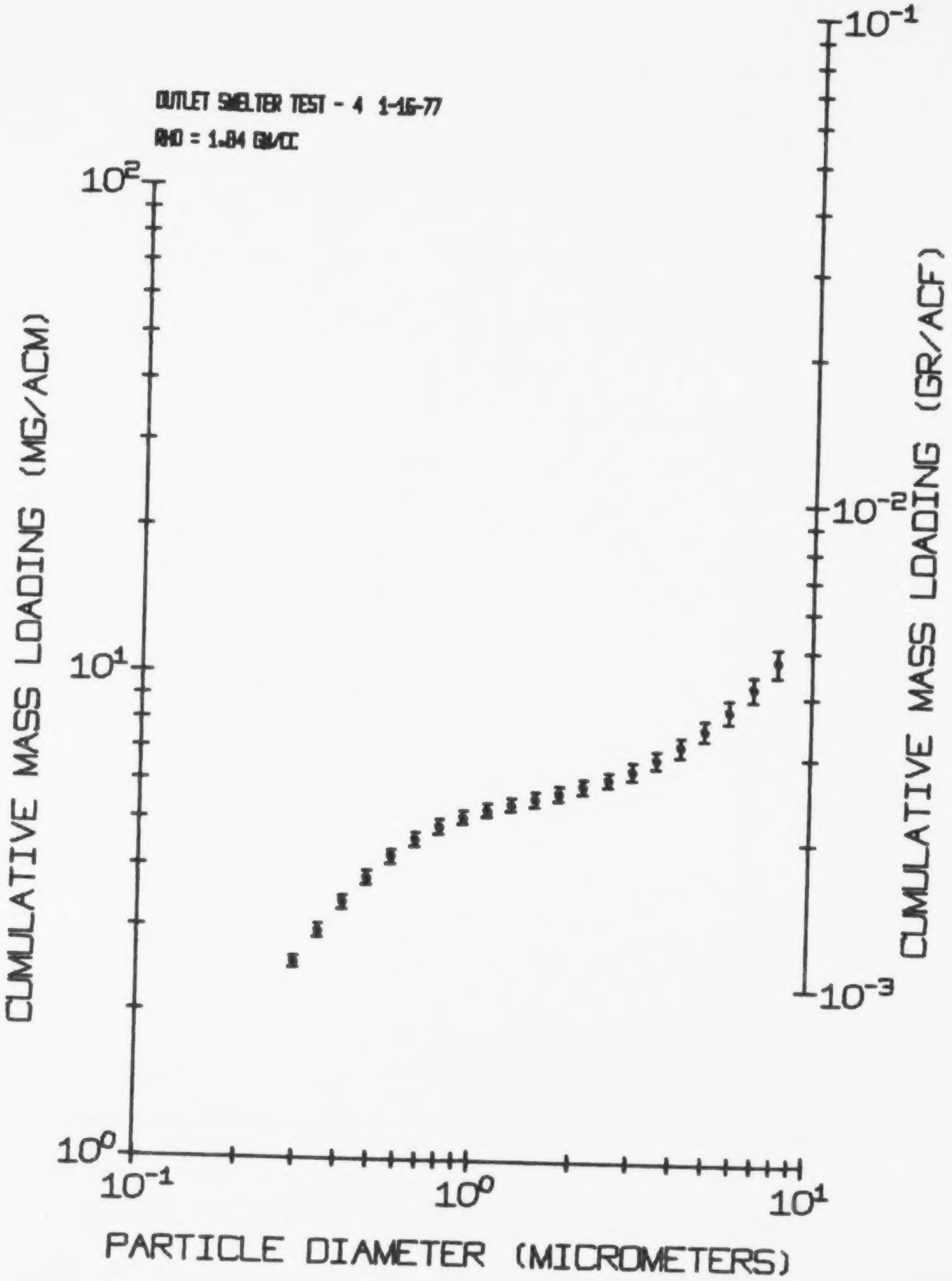

Figure 14. Outlet cumulative mass loading, averaged over the fourth day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

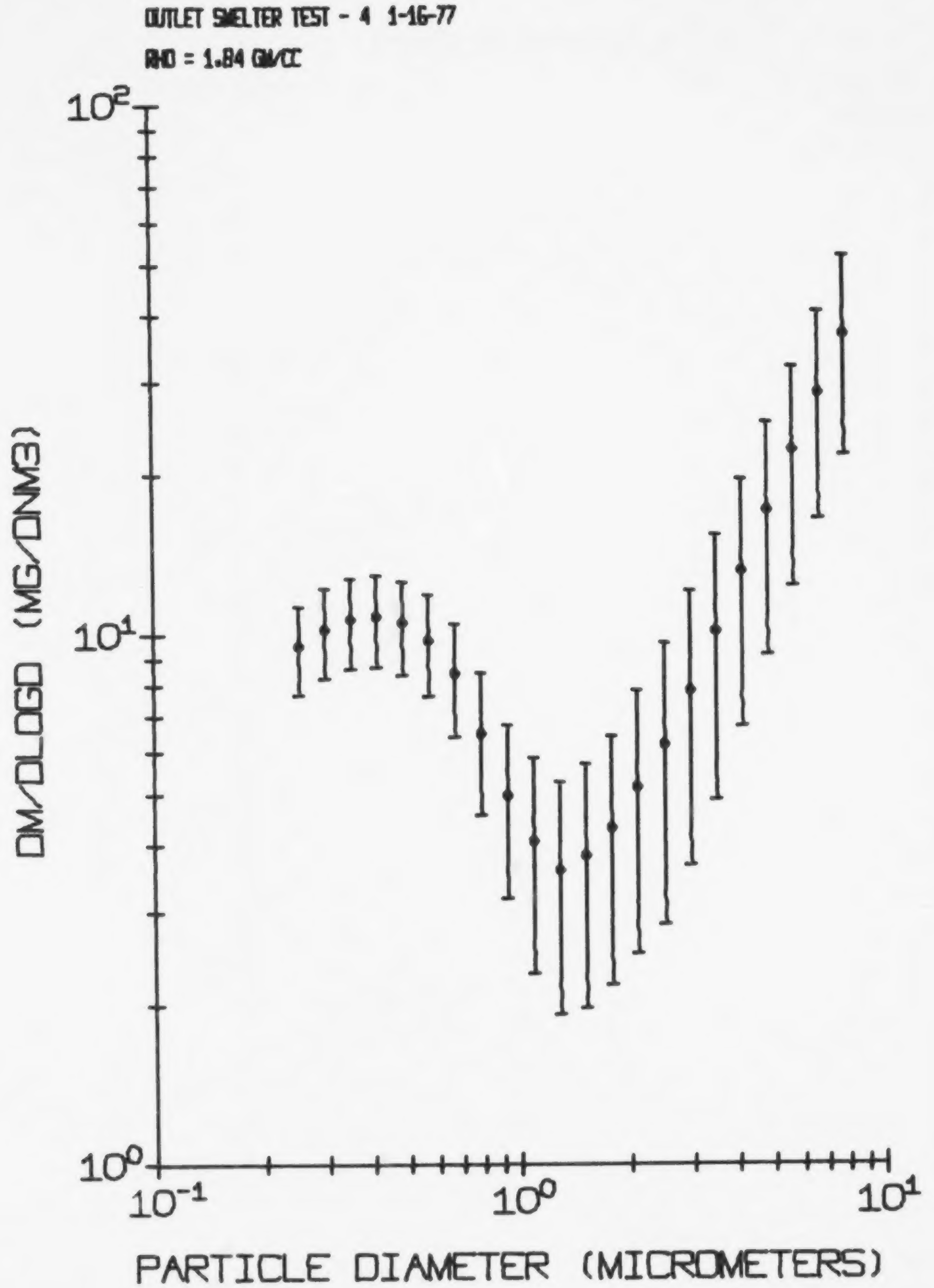

Figure 15. Outlet differential mass concentration (dM/dlogD), averaged over the fourth day of testing, versus Stokes particle diameter. 50% confidence intervals are shown.

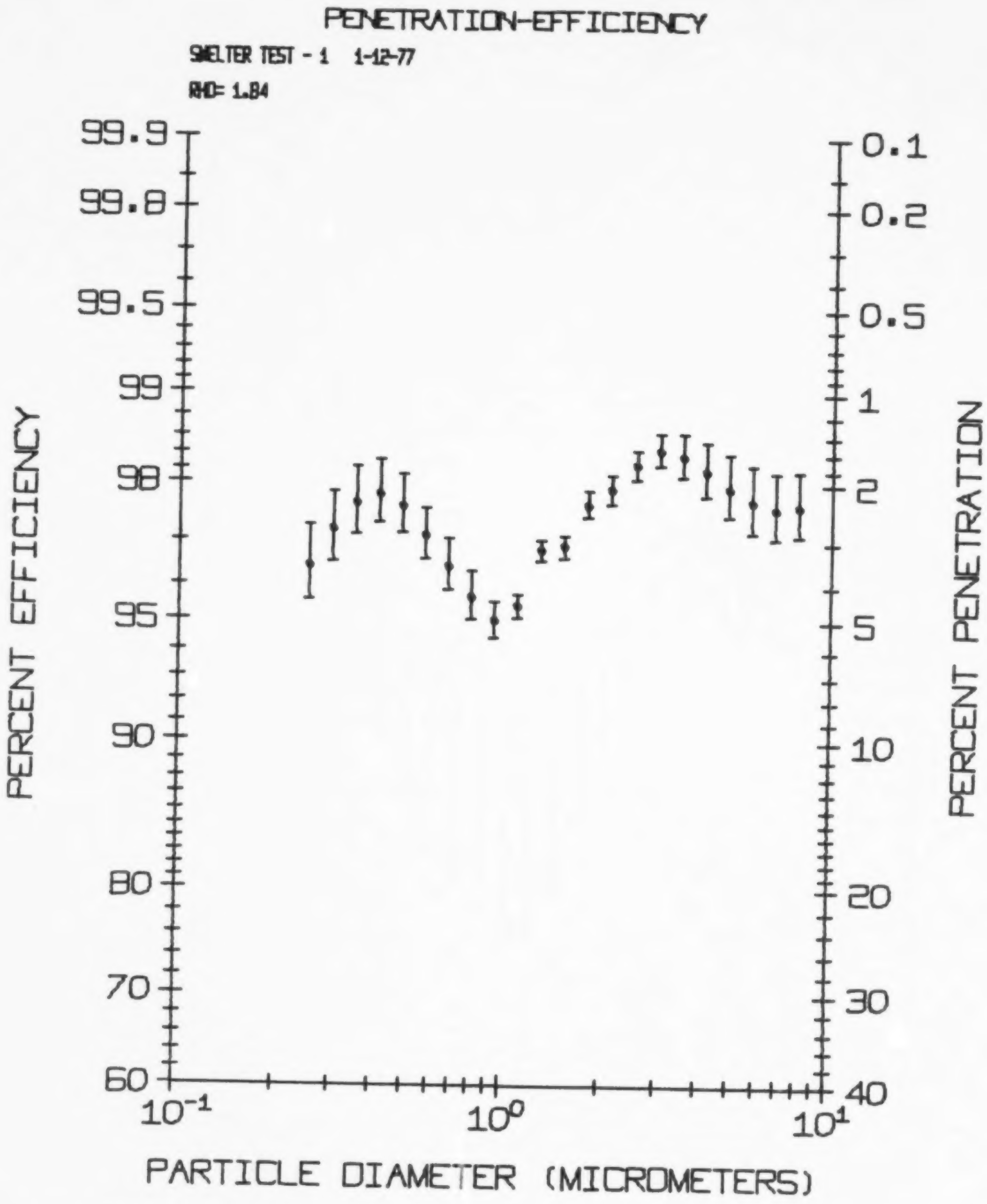

Figure 16. Penetration-efficiency versus Stokes particle diameter for the first day of testing. 50% confidence intervals are shown.

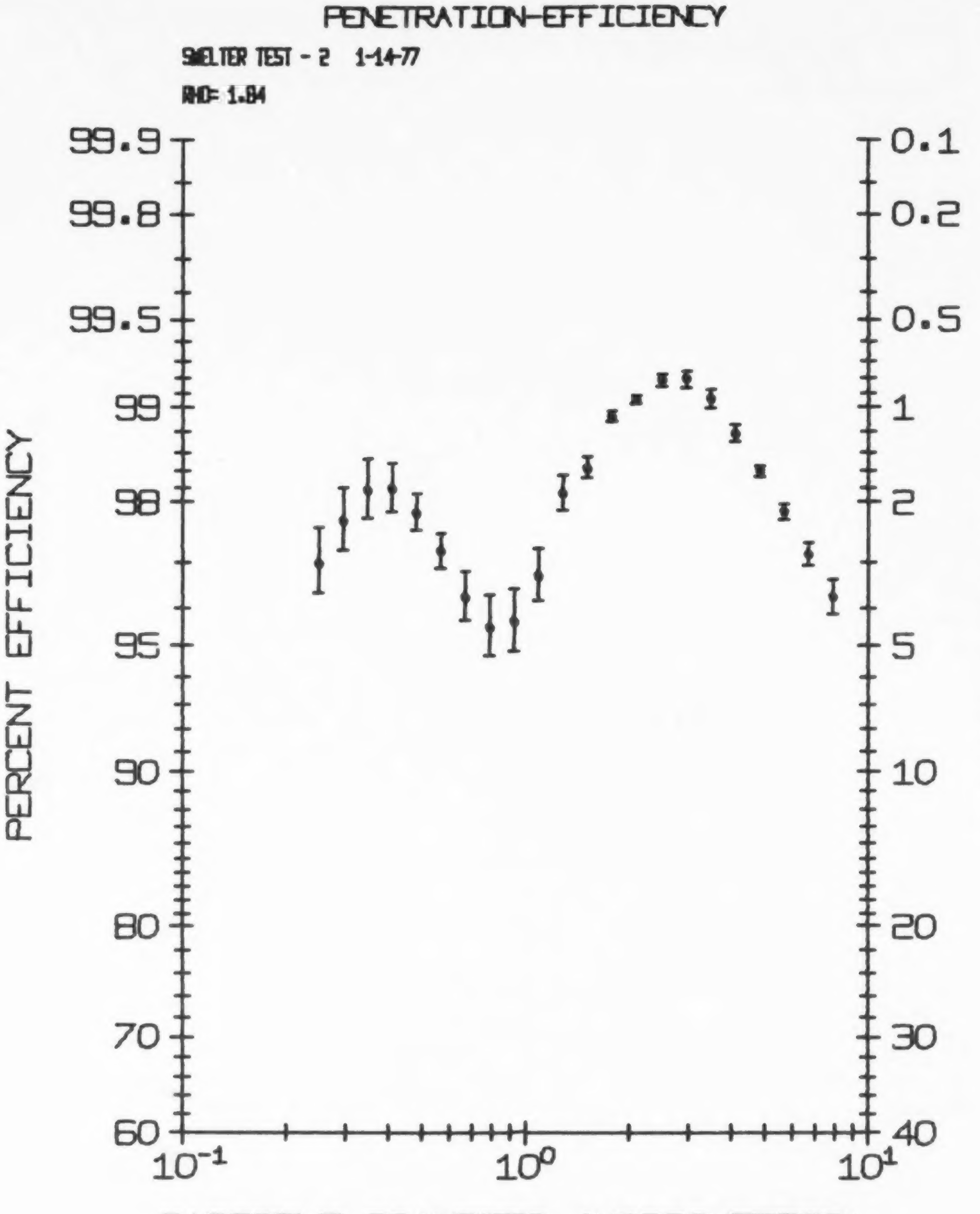

Figure 17. Penetration-efficiency versus Stokes particle diameter for the second day of testing. 50% confidence intervals are shown.

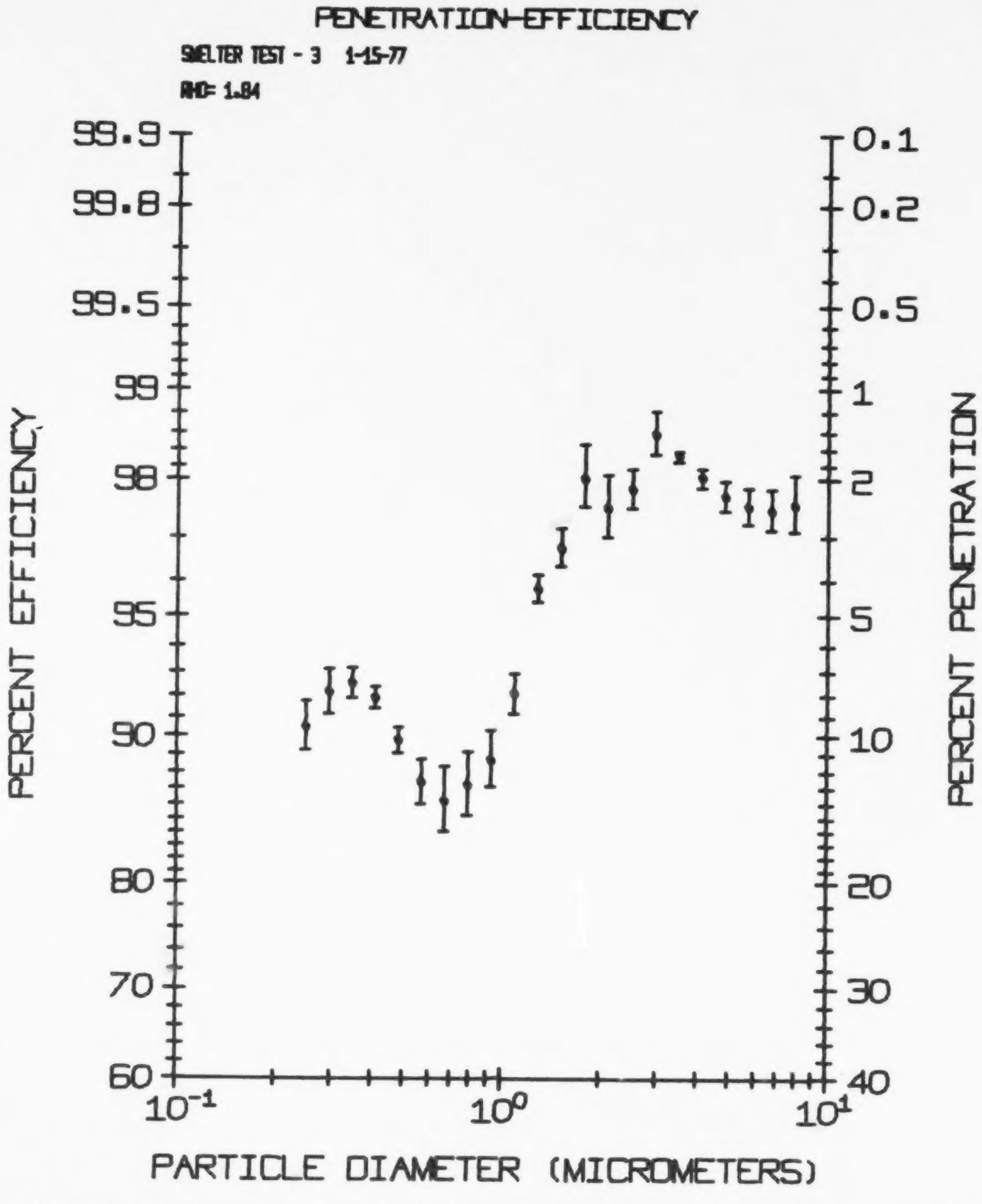

Figure 18. Penetration-efficiency versus Stokes particle diameter for the third day of testing. 50% confidence intervals are shown.

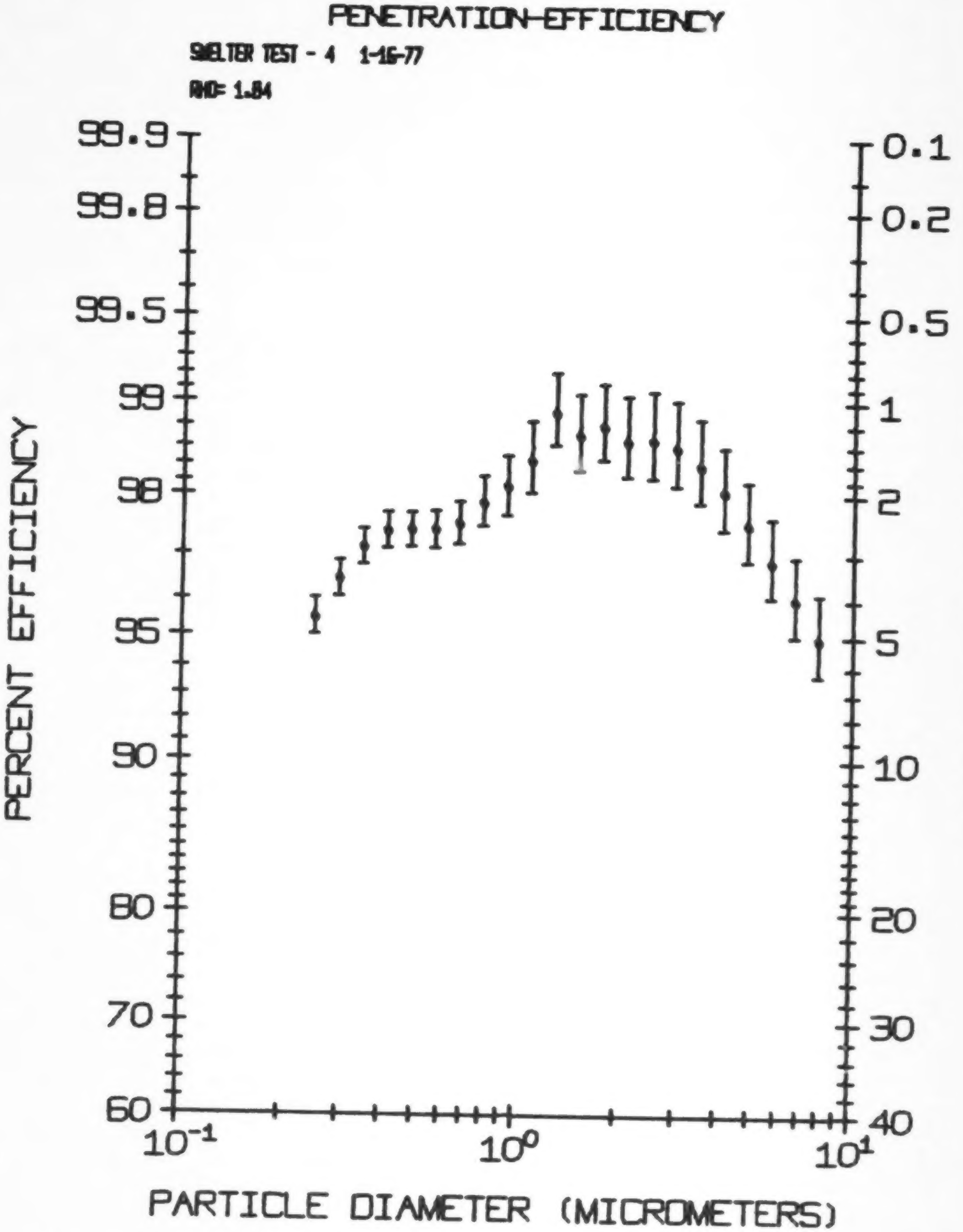

Figure 19. Penetration-efficiency versus Stokes particle diameter for the fourth day of testing. 50% confidence intervals are shown.

diameter in the operating range of the instrument (0.015 to 0.3 μm particle diameter). A diagrammatic representation of this device is shown in Figure 20. A Royco PC 225 mainframe and PC 241 optical sensing unit were used to make the optical single particle light scattering measurements. The useful particle size range of this instrument is approximately 0.3 to 2.0μm (PSL). Particle diameters reported here for the optical counter are not based on equivalent polystyrene latex particle size calibrations as is the usual practice. Rather, a horizonital elutriator was used with the optical counter to determine particle sizes based on gravitational settling. These "settling" diameters are the diameters reported.

Neither of the instruments used in ultrafine particle distribution determinations can tolerate raw flue gases as sample streams nor can they cope with the particle concentrations found in flue gases. Thus, ultrafine measurements are based on extractive sampling with a metered sample being diluted with clean dry air, to both condition the sample and reduce the particle concentrations to levels within the operating limits of the instruments. The required dilution typically ranges from 10:1 to >1000:1 depending on the particle source and the location of the sampling port (i.e., upstream or downstream of the control device). A diagrammatic representation of the Southern Research Institute Sample Extraction and Dilution System (SEDS) in shown in Figure 21.

Inlet ultrafine measurements were made on January 12 and 14, 1977. A total of approximately eight hours of usable data was taken during these two days. The SEDS was used in port 2 and sampling was not done concurrently with the impactors. The sample was extracted from a depth of 3 to 4 feet. No traverses were made.

Figure 22 shows differential size distributions on a number basis for the inlet for January 12 and 14. These results represent a grand average for this period. Similar data obtained with impactors are also shown for comparison purposes. As can be seen, the ultrafine and impactor data do not compare well at the inlet. There could be several reasons for this. First, the samples were single point samples taken at different depths. If there were large concentration gradients or severe stratification, then a poor comparison might result; this, however, is unlikely. Second, the ultrafine and impactor samples were not taken at the same time. Third, there may be cyclic variations in the operation of the reverberatory furnace which have a time period longer than the 30 minute sampling time for the impactors. Fourth, unrecognized sublimation/condensation effects from As_2O_2 and/or H_2SO_4 may have influenced the data through phase changes resulting from the sampling and measurement processes. Day to day reproducibility in the ultrafine inlet data appeared to be good.

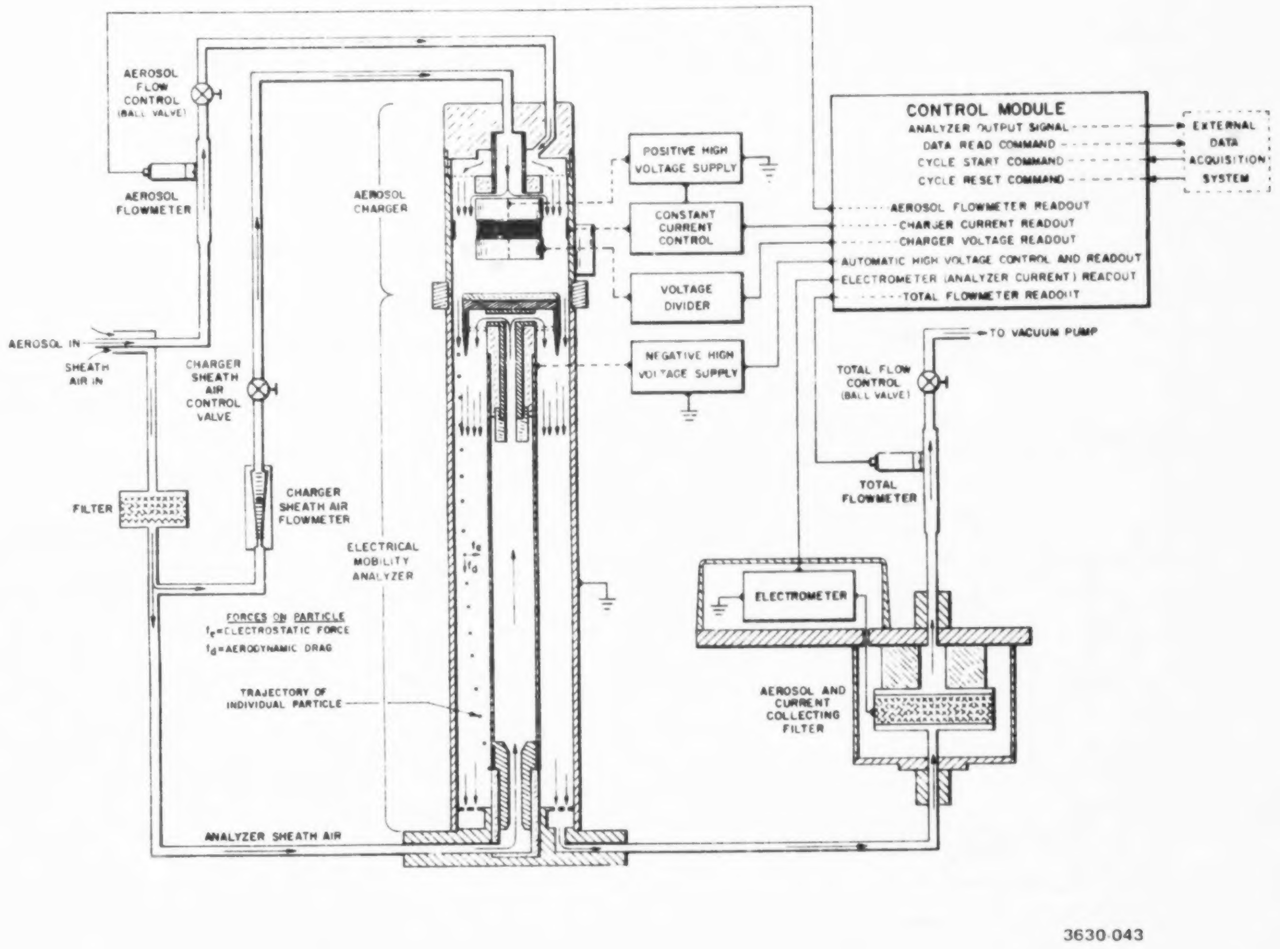
AEROSOL FLOW CONTROL (BALL VALVE)
AEROSOL FLOWMETER
AEROSOL IN
SHEATH AIR IN
FILTER
CHARGER SHEATH AIR CONTROL VALVE
CHARGER SHEATH AIR FLOWMETER
AEROSOL CHARGER
ELECTRICAL MOBILITY ANALYZER
FORCES ON PARTICLE
f_e=ELECTROSTATIC FORCE
f_d=AERODYNAMIC DRAG
f_e
f_d
TRAJECTORY OF INDIVIDUAL PARTICLE
ANALYZER SHEATH AIR
POSITIVE HIGH VOLTAGE SUPPLY
CONSTANT CURRENT CONTROL
VOLTAGE DIVIDER
NEGATIVE HIGH VOLTAGE SUPPLY
CONTROL MODULE
ANALYZER OUTPUT SIGNAL
DATA READ COMMAND
CYCLE START COMMAND
CYCLE RESET COMMAND
AEROSOL FLOWMETER READOUT
CHARGER CURRENT READOUT
CHARGER VOLTAGE READOUT
AUTOMATIC HIGH VOLTAGE CONTROL AND READOUT
ELECTROMETER (ANALYZER CURRENT) READOUT
TOTAL FLOWMETER READOUT
EXTERNAL DATA ACQUISITION SYSTEM
TO VACUUM PUMP
TOTAL FLOW CONTROL (BALL VALVE)
TOTAL FLOWMETER
ELECTROMETER
AEROSOL AND CURRENT COLLECTING FILTER
3630-043

Figure 20. Diagrammatic representation of the Thermosystems Model 3030 Electrical Aerosol Analyzer (EAA).

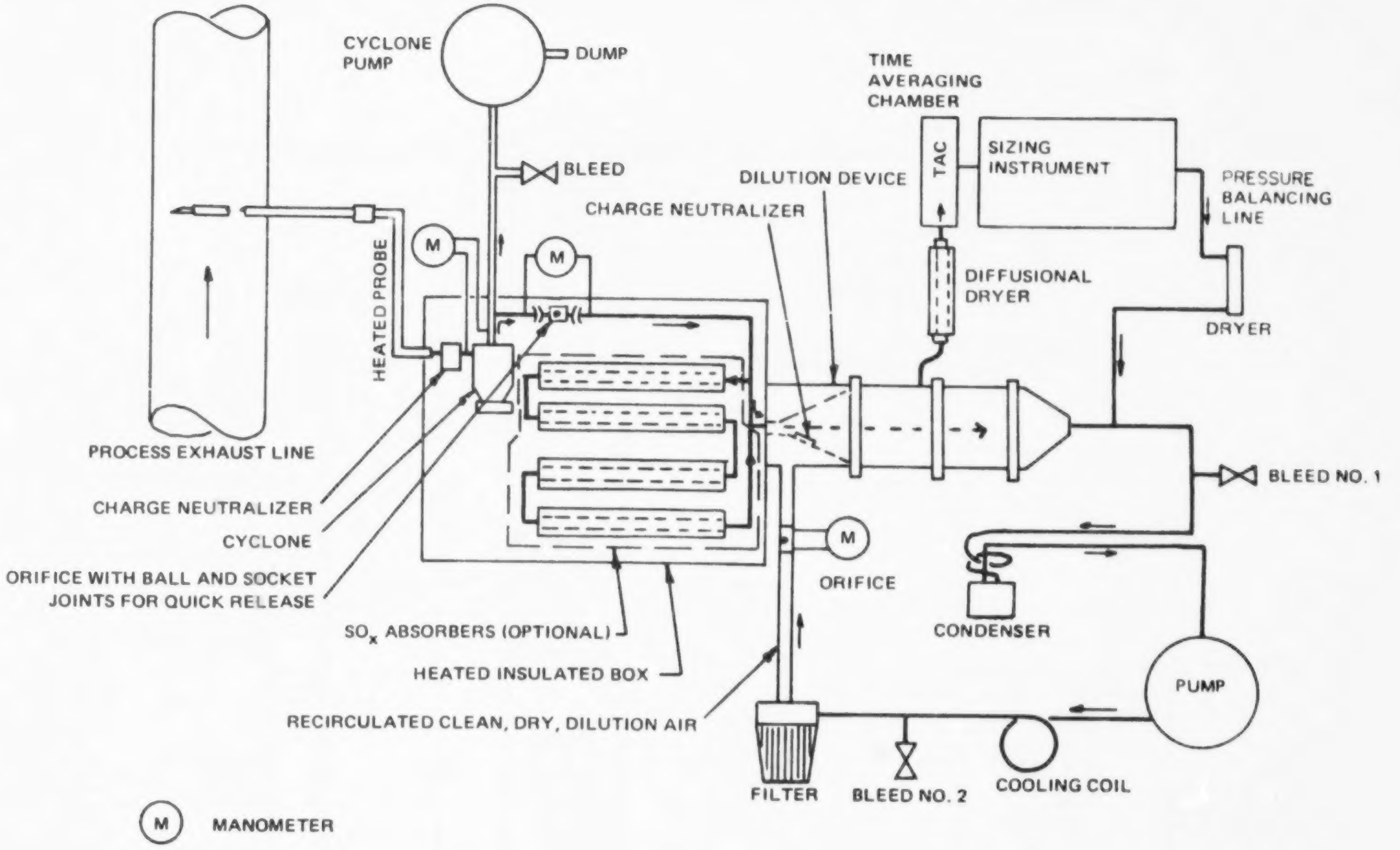

Figure 21. The Sample Extraction and Dilution System (SEDS) designed by Southern Research Institute. Shown in diagrammatic form.

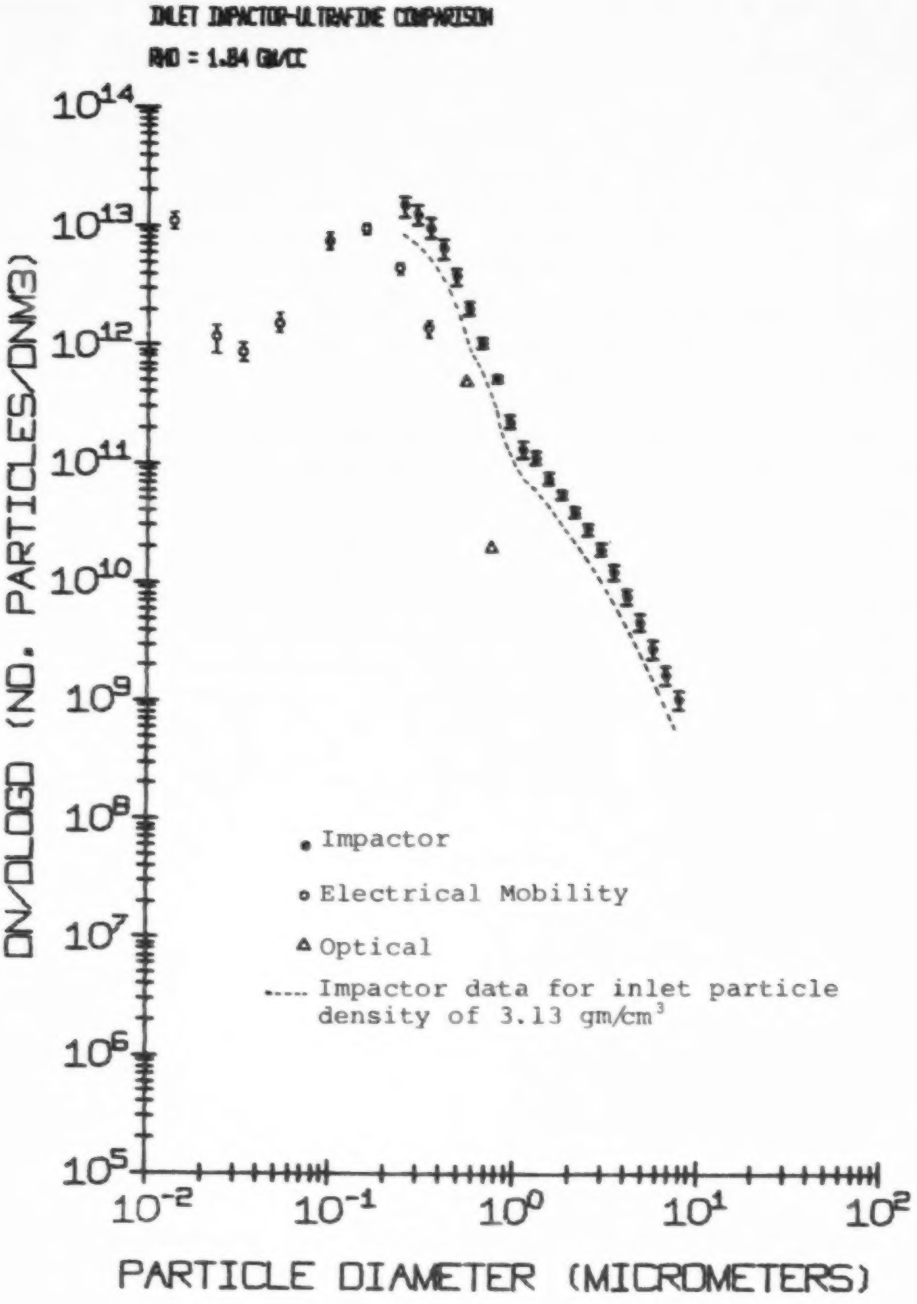

Figure 22. Inlet differential number concentration (dN/dlogD), averaged over inlet tests conducted on January 12 and 14, versus Stokes particle diameter. Data taken by Cascade impactors, optical counters and electrical mobility measurements are shown for comparison. 50% confidence intervals are shown.

Outlet ultrafine particle size distribution measurements were made in port 2 on January 15 and 16, 1977. A total of approximately seven hours of usable data was taken. The sampling point was 3 to 4 feet deep into the duct. As with the impactor data, in contrast to the behavior at the inlet, the outlet ultrafine particle size distribution data differed greatly from day to day, therefore, the agreement between impactor and ultrafine data was examined on a daily basis. Figures 23 and 24 show the outlet dN/dlogD impactor and ultrafine measurements compared for each day's outlet testing. In Figure 20, the agreement is much better than in Figure 24. Any agreement may be fortuitous since the same sampling problems occurred at the inlet. In addition, the impactors and the ultrafine system were using different sampling ports.

Penetration-efficiency estimates in the ultrafine particle size range were calculated by averaging the inlet data taken on January 12 and 14 and comparing this with the outlet data taken on January 15 and 16. This assumes that the inlet concentrations and size distribution remains constant throughout the test series. This assumption appears to be generally valid in this case based on the reproducibility of the ultrafine data during the time it was taken and on the relative invariance of the impactor data. The lack of two instrumentation systems for obtaining ultrafine data necessitated obtaining the data sequentially as was done here. Figures 25 and 26 show the calculated efficiencies versus particle size. Also plotted on Figures 25 and 26 are impactor-based efficiencies for the purposes of comparison.

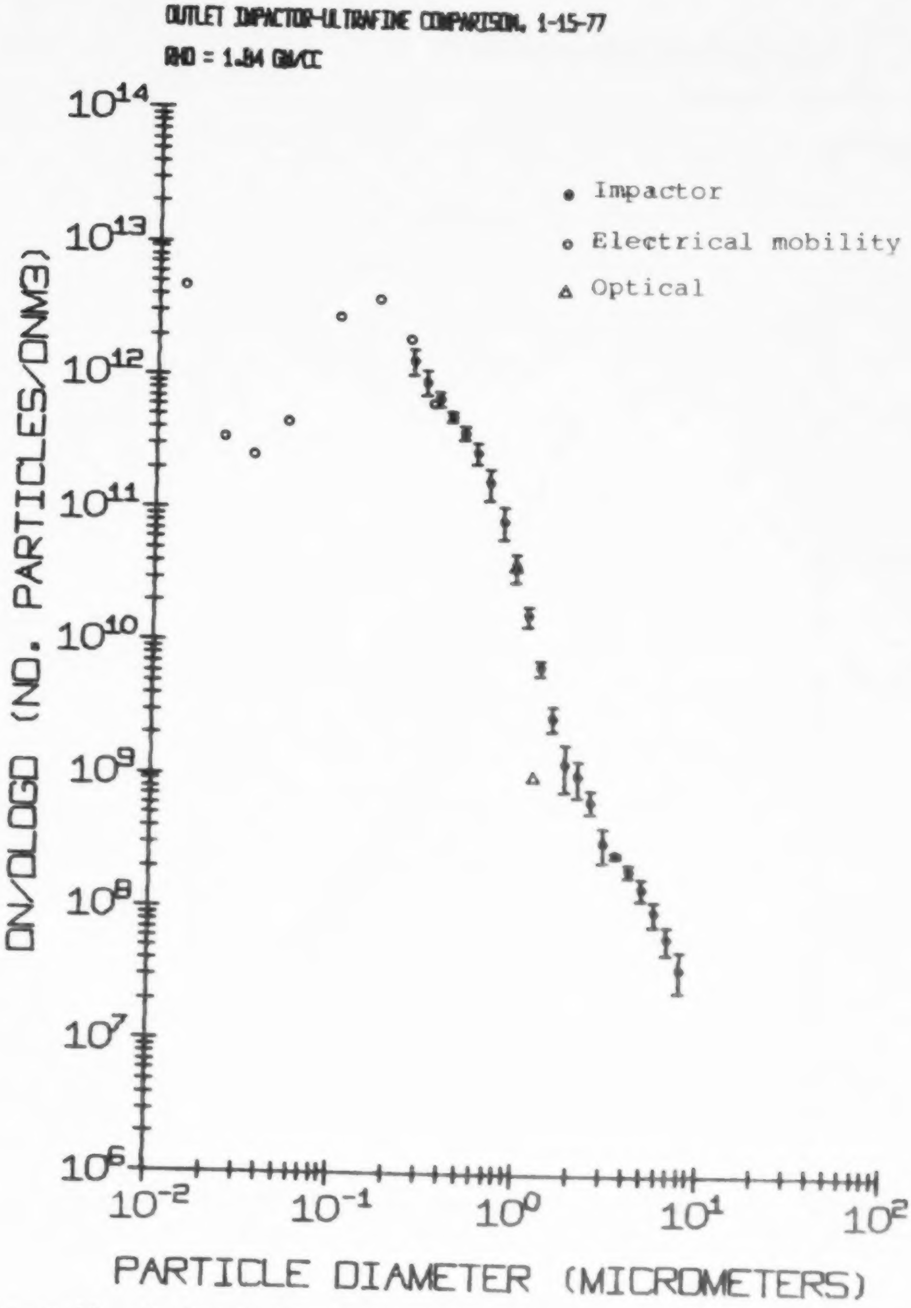

Figure 23. Outlet differential number concentration (dN/dlogD), for January 15, versus Stokes particle diameter. Data taken by Cascade impactors, optical counters, and electrical mobility measurements are shown for comparison. 50% confidence intervals are shown.

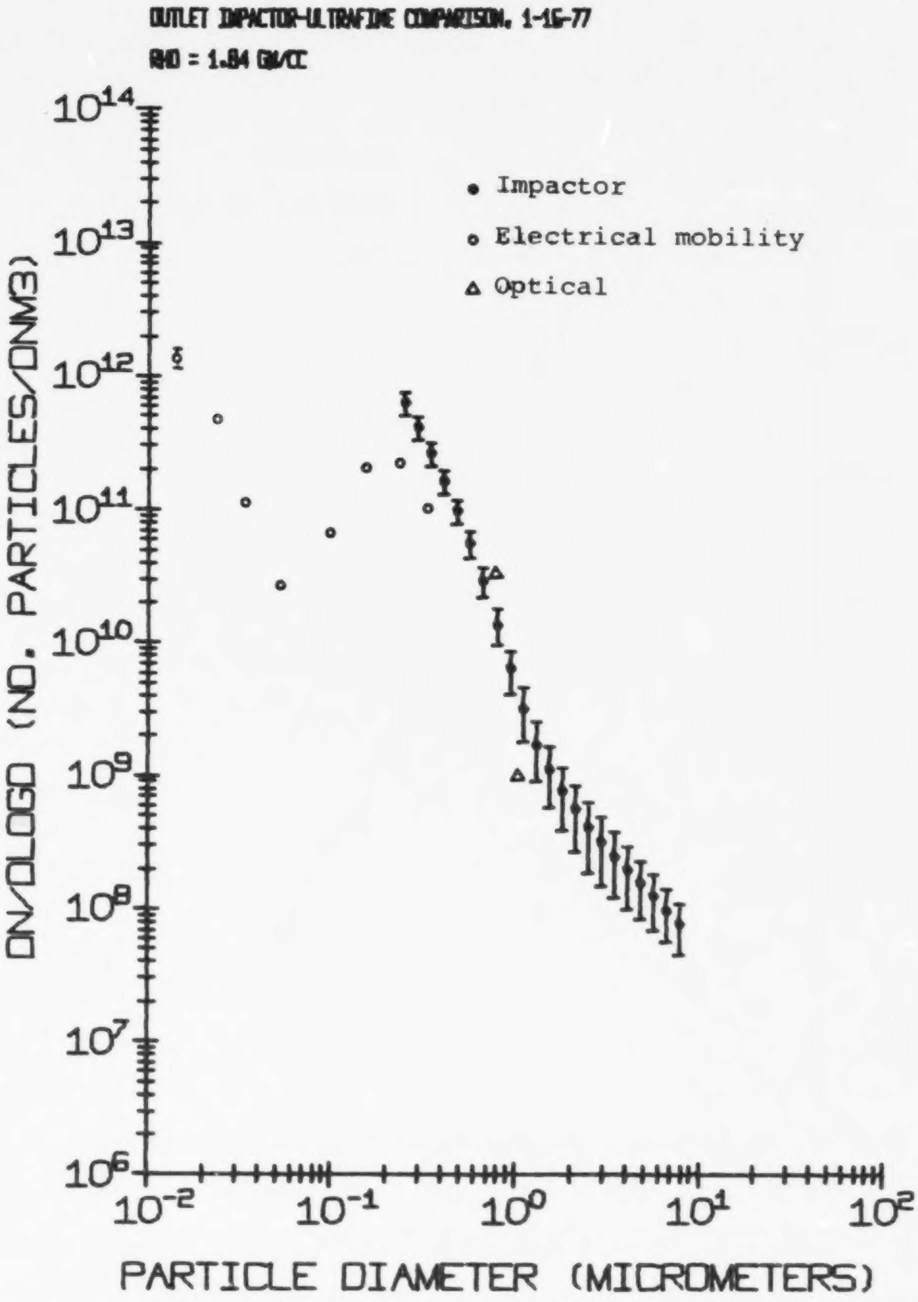

Figure 24. Outlet differential number concentration (dN/dlogD), for January 16, versus Stokes particle diameter. Data taken by Cascade impactors, optical counters, and electrical mobility measurements are shown for comparison. 50% confidence intervals are shown.

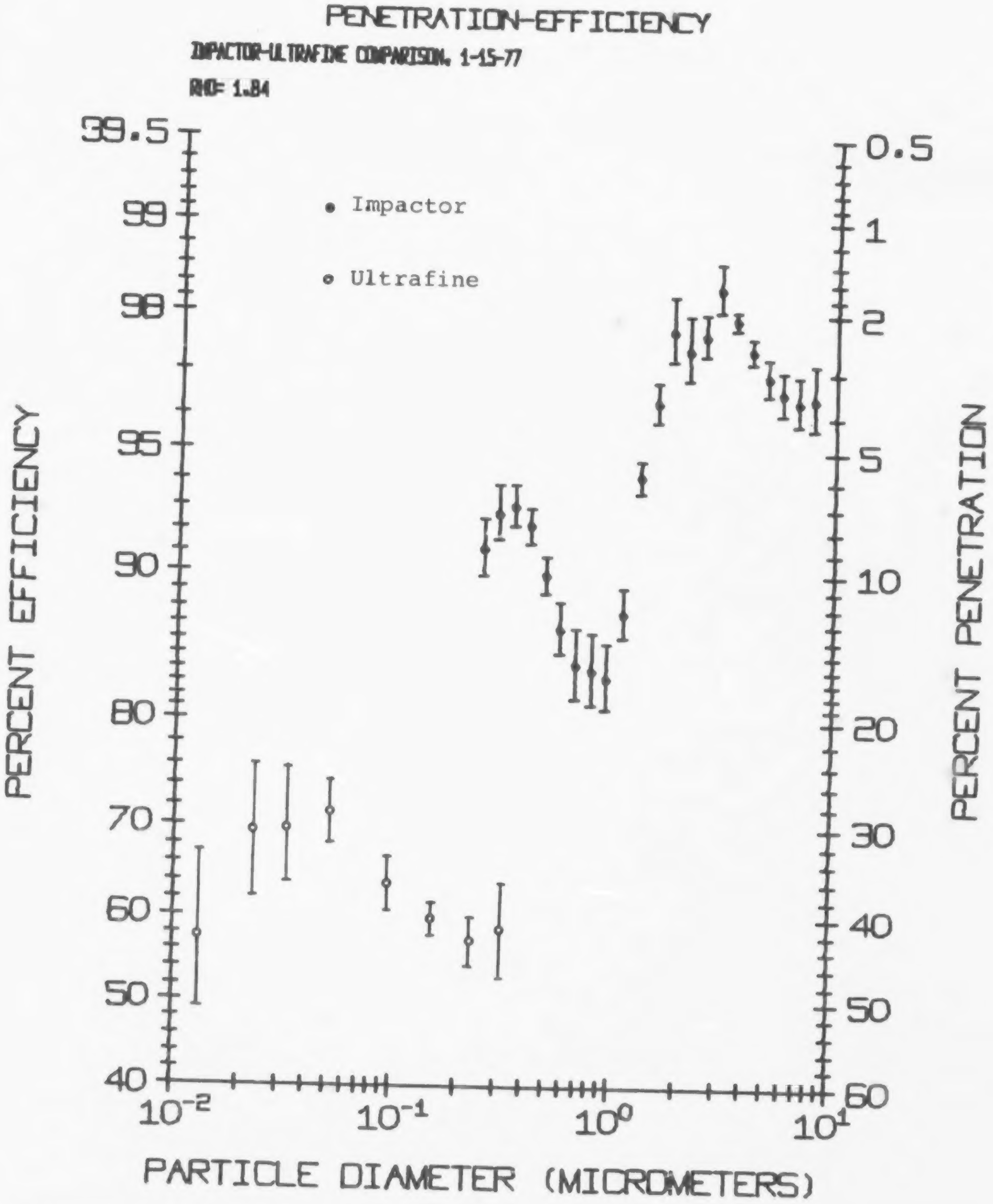

Figure 25. Penetration efficiency versus Stokes particle diameter for January 15. Data taken by Cascade impactors and electrical mobility methods are shown. Inlet data used in these calculations were taken on January 12 & 14. 50% confidence intervals are shown.

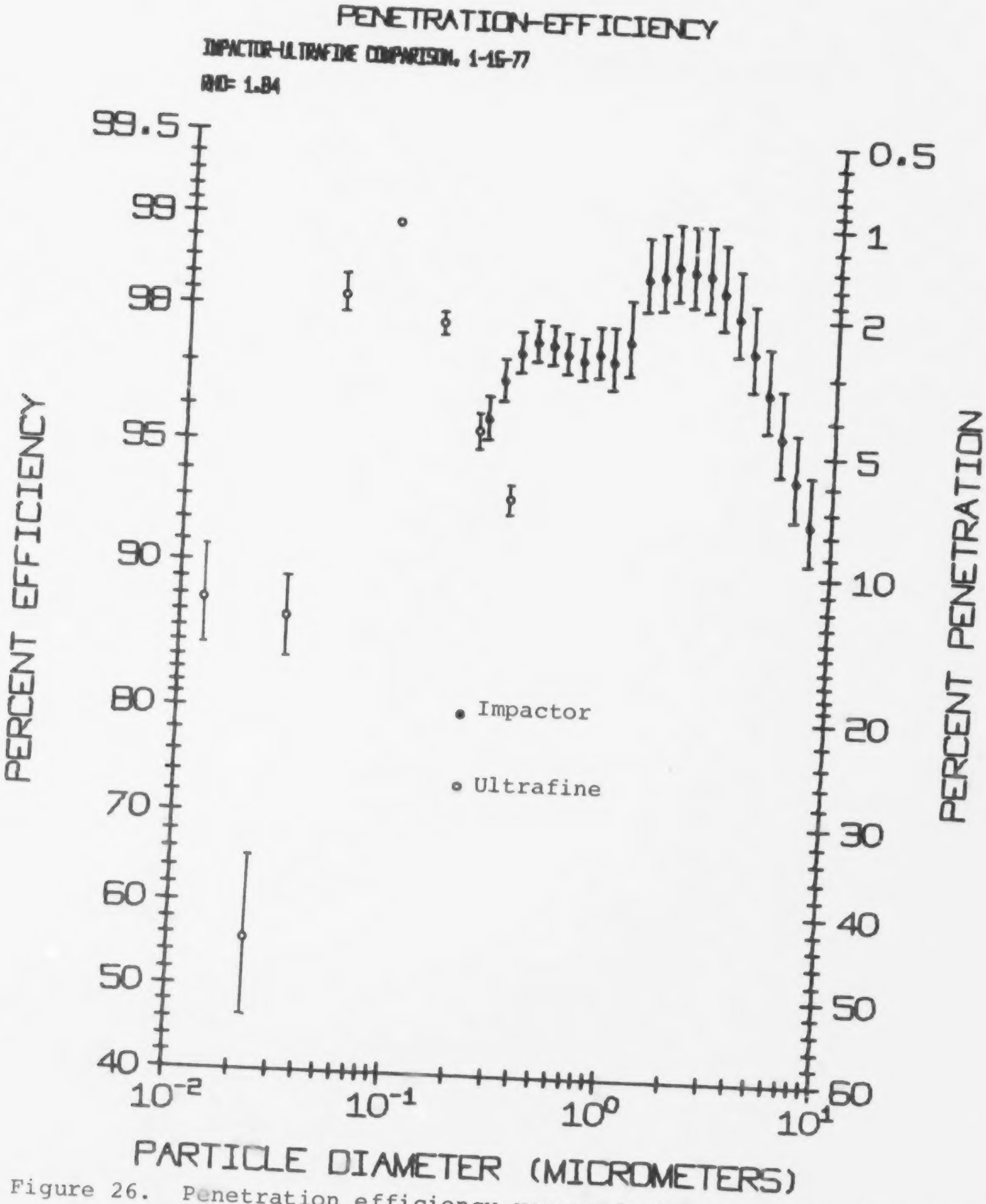

Figure 26. Penetration efficiency versus Stokes particle diameter for January 16. Data taken by Cascade impactors and electrical mobility methods are shown. Inlet data used in these calculations were taken on January 12 & 14. 50% confidence intervals are shown.

SECTION 7

ELECTROSTATIC PRECIPITATOR ELECTRICAL CONDITIONS

The collection efficiency of an electrostatic precipitator is directly related to the electrical condition that exists within the interelectrode space. The electrical conditions are governed by the power supplies that serve to energize the precipitator, by the general mechanical alignment of the various sections, by the electrical resistivity of the particulate, and by the dust buildup conditions on the corona wires and collection electrodes.

The power supplies installed in this precipitator are designed to deliver approximately thirty nanoamperes per square centimeter ($\sim 30 \mu a/ft^2$) and a maximum voltage of approximately sixty kilovolts. These current limits are somewhat low. In those cases where other factors do not limit the performance, current densities of perhaps sixty to seventy nanoamperes per square centimeter may be expected. The electrical energization of the electrostatic precipitator is shown in Figure 27.

The general mechnanical alignment of the electrostatic precipitator could not be evaluated in this installation because this requires a physical inspection of the internals. We were not able to gain access to these internals during the test period since no plant shutdown was scheduled. After a review of the data and considerations of the overall value of that test program to the aims of the research grant, we chose not to make an additional inspection trip to conduct this inspection. If the electrostatic precipitator had been operating acceptably, this inspection would have been performed.

In general, the current density in an operating precipitator increases from inlet to outlet while the secondary voltage decreases from inlet to outlet. This phenomenon is generally caused by the presence of a reasonably high electrical space charge from the fine particles suspended in the inlet gas stream. This suppresses the current and increases the voltage on the inlet fields. As the gas stream proceeds through the ESP the particles are collected, reducing the space charge, allowing the current to increase while the voltage decreases.

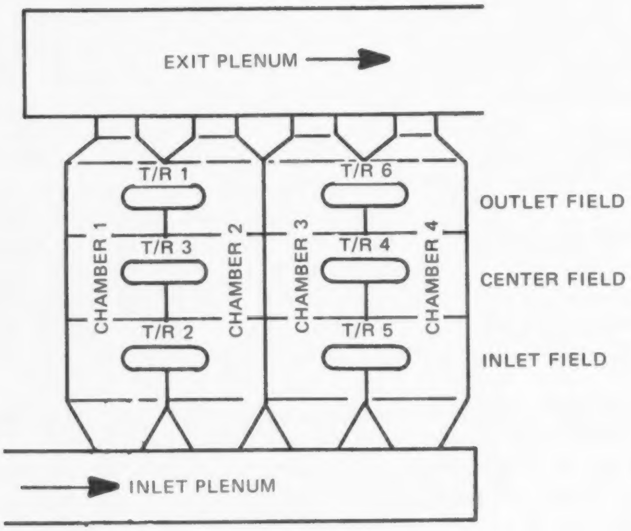

Figure 27. Electrostatic Precipitator Configuration.

This condition was approximately obtained on January 13 through January 15, 1977. However, there was a significant variation in the electrical conditions within this period. (See Figures 28, 29, and 30). The general shape of the curves are correct, but there exists the possibility of dust buildup on the electrodes and/or mechanical misalignment within the field.

An anomaly was noted on January 15. All sets exhibited an unusually high corona start voltage on this day. This suggests a possible dust buildup on the corona electrode, leading to an increase in the effective corona wire diameter.

The voltage vs. current curves for the morning and evening of January 16 are shown in Figures 31 and 32. The voltage-current curves in the morning (Figure 31) had a normal configuration; however, the inlet curve in the evening (Figure 32) shows a higher current than either the middle or outlet field, in contrast to what is expected. A possible explanation for this increase in current in the inlet field is a buildup of material on the insulators that support and act as guides for the corona frame. This buildup provided a parallel resistive leakage path to ground for this field.

The electrical conditions were highly variable during the test period. Current densities in specific fields tended to change from day to day. These changes suggest a significant variation in particulate and gas loadings and dust buildup conditions over the test period. See Table 3 on page 14 for the electrical operating log during the test period.

The electrical resistivity was measured with an E.P.A. high temperature in situ probe. This probe has been modified for use in temperatures encountered in smelter operations and for hot side electrostatic precipitators in the Electric Utility Industry. During this test period, fuel oil was fired in the reverberatory furnace. The values obtained from these measurements are given below.

Date	Time	Temp °C	Resistivity -ohm·cm	Cell Depth cm
1/11/77	1600	238	8.0×10^{9}	0.06
1/12/77	0900	238	1.5×10^{10}	0.11
1/12/77	1100	227	5.5×10^{9}	0.09
1/12/77	1450	246	7.6×10^{7}	0.16
1/14/77	1130	241	7.4×10^{8}	0.06
1/15/77	1015	254	5.1×10^{10}	0.12
1/16/77	0830	243	1.7×10^{9}	0.06

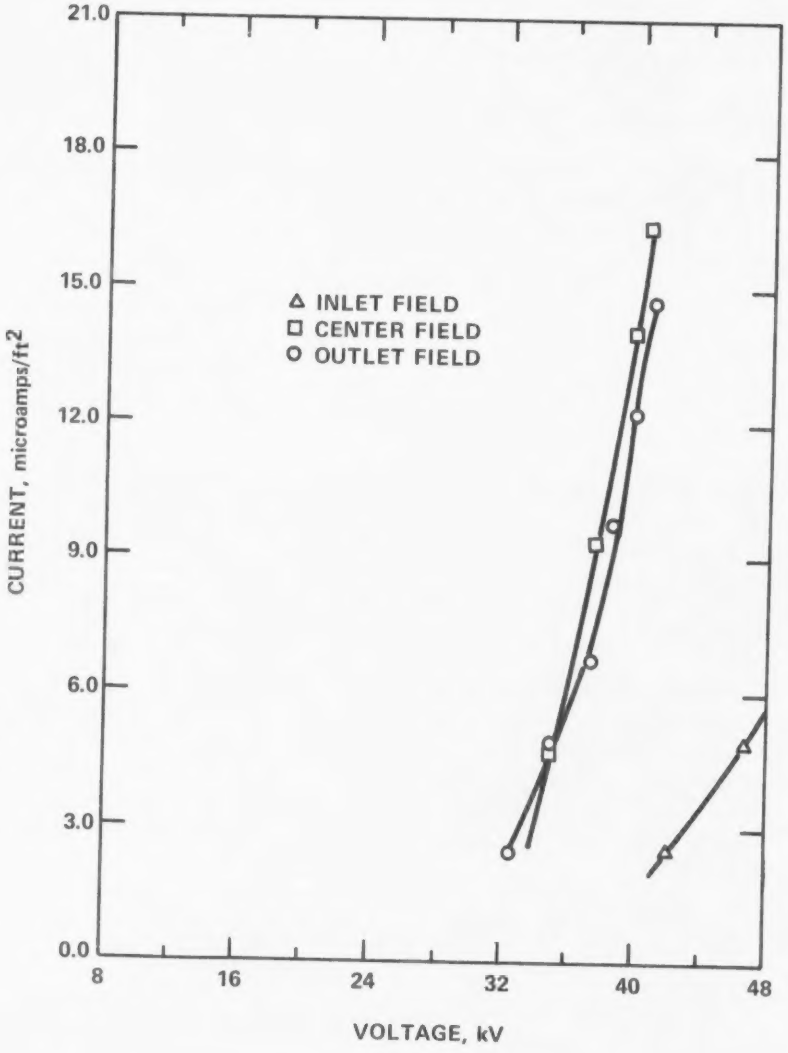

Figure 28. Voltage-current curves, January 13, 1977.

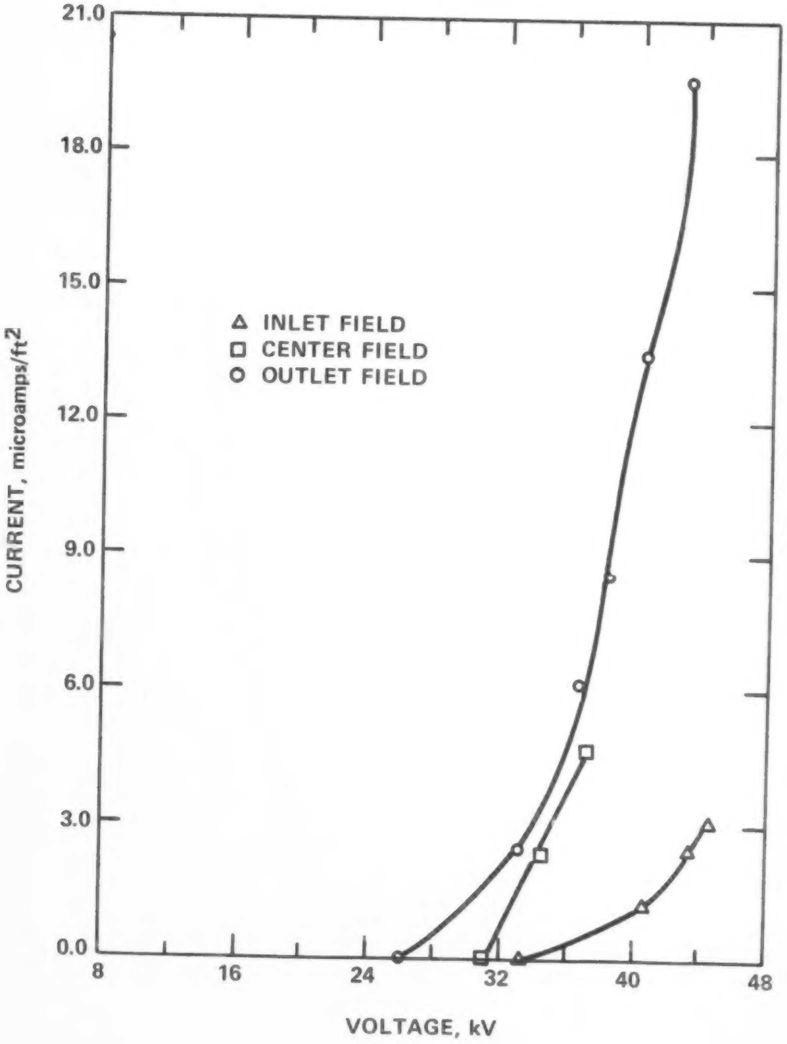

Figure 29. Voltage-current curves, January 14, 1977.

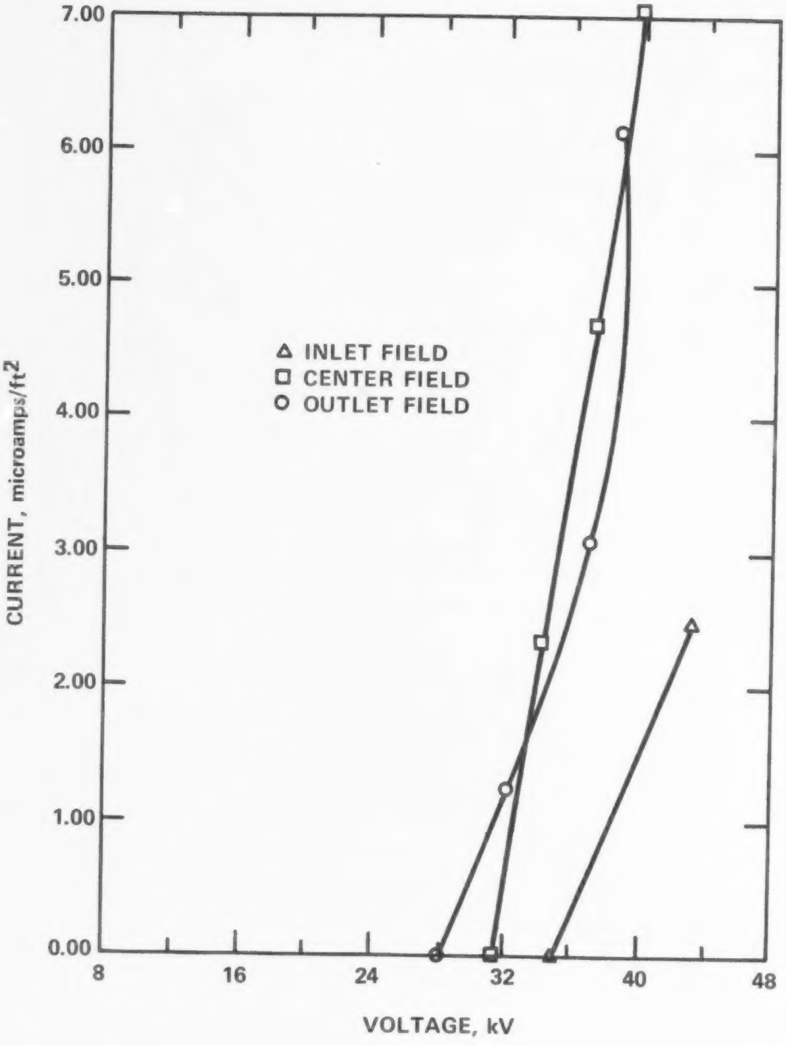

Figure 30. Voltage-current curves, January 15, 1977

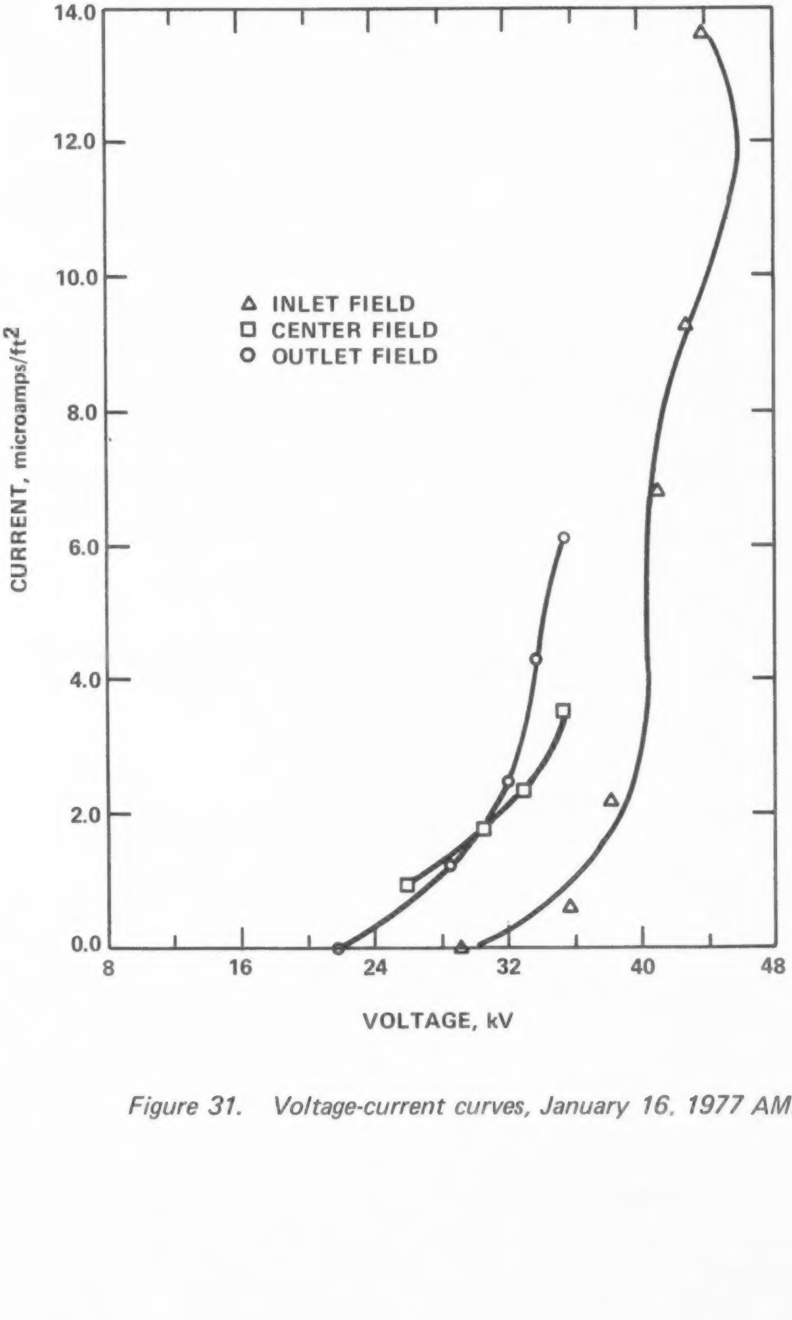

Figure 31. Voltage-current curves, January 16, 1977 AM.

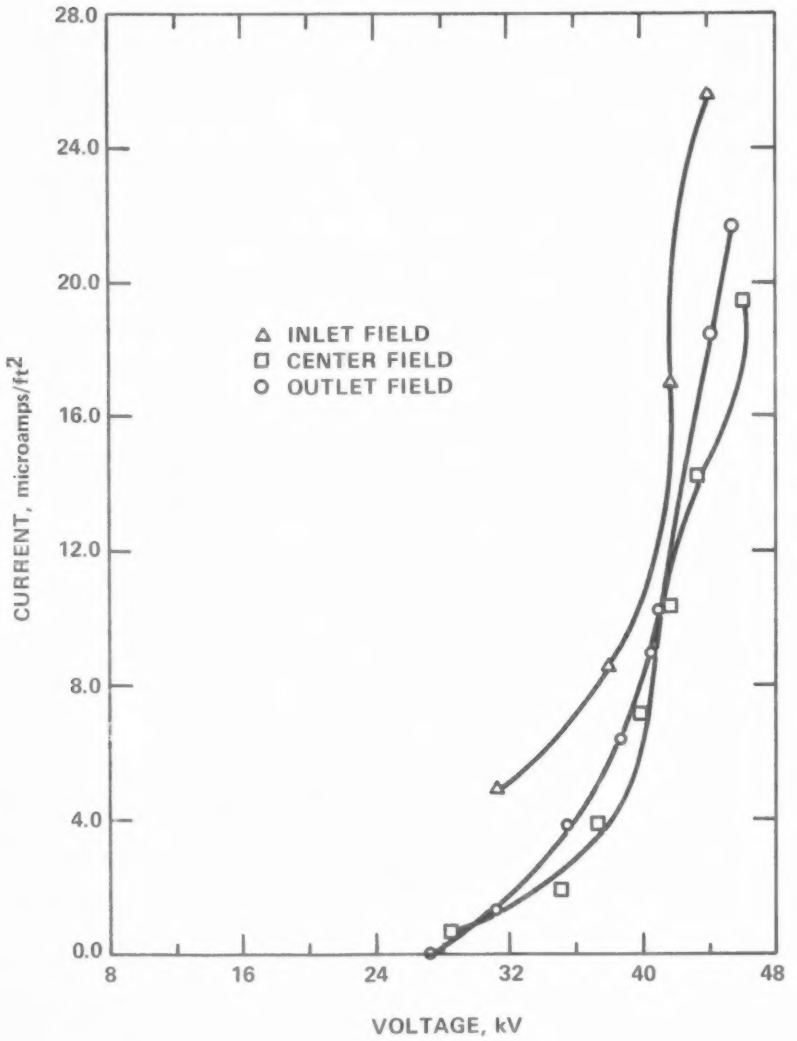

Figure 32. Voltage-current curves, January 16, 1977 PM.

The range of resistivities are such that resistivity does not limit the performance of this electrostatic precipitator when firing oil.

Some measurements were made at an earlier time when gas was fired. These values (shown below) are somewhat higher and may tend to cause electrical sparkover during normal operation.

Date	Time	Temp °C	Resistivity -ohm·cm	Cell Depth cm
12/8/76	0845		No Test	
12/8/76	1050	279	8.1×10^{11}	0.06
12/8/76	1255	307	7.0×10^{10}	0.07
12/8/76	1555	316	1.6×10^{12}	0.08
12/9/76	0815	338	1.6×10^{11}	0.05
12/9/76	-	-	6.3×10^{10}	0.09
12/9/76	1145	338	7.6×10^{10}	0.07

SECTION 8

MATHEMATICAL MODELING

UTILIZATION OF TEST DATA

One objective of the test program was to acquire representative data concerning the gas stream and the operation of the precipitator in order to test the extent of applicability of the existing mathematical model of electrostatic precipitation. If the predictions of the model show good agreement with the test data under the measured conditions, then the model can be used to predict precipitator performance under other specified operating conditions in order to obtain effective precipitator sizing. If the predictions of the existing model fail to give satisfactory agreement with the test data, then the test data can be utilized to establish where the model is unsatisfactory and to develop a more appropriate model for smelter precipitators.

The data acquired during the test program have been utilized in two ways in conjunction with the mathematical model of electrostatic precipitation. First, certain test data have been used as input parameters for the model. These measured input parameters include the inlet mass loading and particle size distribution, electrical operating conditions, the gas volume flow rate, temperature, and pressure, and the electrical resistivity of the particulate. The mathematical model can predict precipitator performance based on these measured input parameters and the known precipitator geometry. Secondly, certain test data have been utilized for making comparisons with the predictions of the mathematical model. These data include the inlet and outlet mass loadings and particle size distributions from which overall mass and fractional collection efficiencies can be determined.

DESCRIPTION OF THE MODEL

Under the sponsorship of the Environmental Protection Agency, Southern Research Institute has developed a theoretically based mathematical model of the electrostatic precipitation process.* The model was developed from coal-fired utility data.

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*J. P. Gooch, J. R. McDonald, and S. Oglesby, Jr. A Mathematical Model of Electrostatic Precipitation. Environmental Protection Technology Series, Publication No. EPA-650/2-75-037 (April, 1975).

The mathematical operations and calculations in the model are performed by a computer program. The most important input data to the program are (1) the measured particle size distributions of the inlet dust, (2) the current and voltage to each series field, (3) precipitator geometry, and (4) gas flow. The computer program divides the precipitator into length increments in the direction of gas flow and calculates the electric field distribution, and the particle charge, particle migration velocity, and collection efficiency as a function of particle diameter for each length increment.

Electric Field Calculation

Since the particle migration velocity is a function of the electric field at the plate, it is necessary to calculate the electric field adjacent to the collection electrode. The method employed for this calculation is a numerical technique introduced by Leutert and Böhlen.* The equations which must be solved are written in discrete form in two dimensions as

$$\frac{\Delta^2 V}{\Delta x^2} + \frac{\Delta^2 V}{\Delta y^2} = \frac{-\rho}{\varepsilon_0} \quad , \text{ and}$$

$$\rho^2 = \varepsilon_0 \left(\frac{\Delta V}{\Delta x}\frac{\Delta\rho}{\Delta x} + \frac{\Delta V}{\Delta y}\frac{\Delta\rho}{\Delta y}\right) \quad ,$$

where

ρ = space charge, coul/m^3
y = distance parallel to gas flow from wire to wire, m
x = distance perpendicular to gas flow from wire to plate, m
ε_0 = permittivity of free space, $\text{coul}^2/(\text{N-m}^2)$ and
V = potential, volts.

The computer model uses a subroutine which iterates on a grid of electric field and space charge density until convergency is obtained. Following convergence, an electric field profile is available which is applicable to the voltage and current existing in the length increment under consideration, and which is consistent with the assumptions and boundary conditions used in the solution.

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*G. Leutert and B. Böhlen, "The Spatial Trend of Electric Field Strength and Space Charge Density in Plate-Type Electrostatic Precipitators." Staub 32 (7):27 (July, 1972).

Charging Rate Calculation

Calculation of particle charge is accomplished by using a model developed by Smith and McDonald.* The model in differential form is

$$\frac{dq}{dt} = \frac{N_0 b_i n_s e^2}{4\varepsilon_0} \left(1 - \frac{n}{n_s}\right)^2 + \frac{\pi a^2 \tilde{v} N_0 e}{2} \int_{\theta_0}^{\pi/2} \exp - \left[\left(\frac{ne^2 (r_0 - a)}{4\pi\varepsilon_0 kTar_0}\right.\right.$$

$$\left.\left. + \frac{[3ar_0^2 - r_0^3 (K+2) + a^3 (K-1)]\ eE_0 \cos\theta}{kTr_0^2 (K+2)}\right)\right] \sin\theta d\theta$$

$$+ \frac{\pi a^2 \tilde{v} N_0 e}{2} \exp(-ne^2/4\pi\varepsilon_0 akT) \quad ,$$

where

q = charge, coulombs

t = time, seconds

N_0 = undisturbed ion concentration, #/m^3

b_i = ion mobility

e = electronic charge, coulombs

n = number of charges on particle

n_s = number of charges on particle at saturation due to field charging mechanism

$n_s = (1 + 2\frac{K-1}{K+2})\ E_0 a^2/e$

a = particle radius, m

K = particle dielectric constant

E_0 = external field, Volts/m

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*W. B. Smith and J. R. McDonald, "Development of a Theory for the Charging of Particles by Unipolar Ions." J. Aerosol Sci., Vol. 7, pp. 151-166 (1976).

k = Boltzmann's constant, joules/°K

T = absolute temperature, °K

r_0 = point at which radial component of electric field is zero

$\tilde{v}$ = mean thermal speed of ions, m/sec.

This equation is integrated numerically using the quartic Runge-Kutta method. The model reduces to the classical diffusion charging equation in the absence of an applied electric field and approaches the results obtained from the classical field charging equation for large particles and large values of electric fields. This calculation is also performed by a subroutine of the computer model. When the calculation is complete for each length increment, values of particle charge are available for all particle sizes represented in the input particle size distribution histogram for use in the subsequent collection calculations.

Particle Collection Calculation

The next step in calculating theoretical collection efficiency is the calculation of the electrical drift velocity or migration velocity resulting from the coulomb and viscous drag forces acting upon a suspended particle. For particle sizes and electrical conditions of practical interest, the time required for the particle to achieve the steady state value of velocity is negligible, and the migration velocity is given by:

$$w = \frac{qE_pC}{6\pi a\mu}$$

where

w = migration velocity of a particle of radius a, m/sec

q = charge on particle, coul

E_p = electric field near the collection electrode, volt/m

a = particle radius, m

μ = gas viscosity, kg/m-sec

C = Cunningham correction factor

$= (1 + A\lambda/a)$

where

$$A = 1.257 + 0.400 \exp(-1.10a/\lambda)$$

and

λ = mean free path of gas molecules, m.

The computer model uses the Deutsch equation to predict the collection fraction η_{ij} for the ith particle size in the jth incremental length of the precipitator. Thus, the Deutsch equation is applied in the form

$$\eta_{ij} = 1 - \exp(-w_{i,j}A_j/Q),$$

where

$w_{i,j}$ = migration velocity of the ith particle size in the jth increment

A_j = collection plate area in the jth increment

Q = volumetric flow rate.

The fractional efficiency η_i for a given particle size over the entire length of the precipitator is determined from

$$\eta_i = \frac{\sum_j \eta_{ij} N_{i,j}}{N_{i,1}}$$

where $N_{i,j}$ is the number of particles of the ith particle size per cubic meter of gas entering the jth increment. The quantity $N_{i,j}$ can be written in the form

$$N_{i,j} = N_{i,j-1} - [1 - \exp(-w_{i,j-1}A_{j-1}/Q)]N_{i,j-1}$$

where $N_{i,1} = N_{i,0}$, the number of particles of the ith particle size per cubic meter of gas in the inlet size distribution. The overall collection efficiency η for the entire polydisperse aerosol is obtained from

$$\eta = \sum_i \eta_i P_i$$

where P_i is the precentage by mass of the ith particle size in the inlet size distribution.

After convergence on the overall mass efficiency has been obtained, the program calculates effective or length averaged migration velocities for the different particle sizes from the Deutsch equation:

$$w_e = \frac{Q}{A_T} \ln \left(\frac{1}{1-\eta}\right)$$

where

w_e = effective migration velocity of particle of radius a, m/sec

A_T = total collecting area

η = collecting fraction for given particle size over total length.

The model contains empirical correction factors which are used as multipliers on the ideally-calculated effective migration velocities in order to account for the nonideal effects of gas velocity distribution, gas sneakage, and particle reentrainment. These correction factors are based either on very simplifying assumptions or limited data and are intended only to give a rough estimate of the degradation in precipitator performance caused by these nonideal conditions.

MODELING OF KENNECOTT PRECIPITATOR

For several reasons, the field test data obtained from measurements on the Kennecott precipitator were not suitable for use in the existing precipitator performance model or for use in developing a model which can be applied to the smelter industry. The Kennecott installation was not representative of a well-functioning precipitator and data which are vital to the modeling effort were not obtained due to constraints placed on the measurements which could be made.

From the standpoint of a modeling effort, the following problems were associated with the evaluation of precipitator performance at the Kennecott installation: (1) all inlet size distribution measurements were obtained at the same location and this location should produce a measured size distribution which is prejudiced towards the finer size range due to physical constraints at the sampling site; (2) considerable uncertainty exists in the flow rate measurements; (3) the precipitator had considerable inleakage of air (estimated to be 40% based on data in Table 11) and a large temperature drop from the inlet to the outlet of well over 100°F; (4) during all of the testing, significant fractions of the precipitator suffered electrical outage; (5) no determination of the gas velocity distribution was made at the inlet of the precipitator, again due to physical constraints at the sampling site; and (6) no data were obtained to gauge the effect of rapping losses on total emissions.

Due to the serious problems mentioned above, it does not appear to be sensible to attempt to model the performance of the Kennecott precipitator during the test period. Instead, it seems to be more reasonable to attempt to project how the precipitator would perform if it were operating properly. This type of projection has been made using the E.P.A.-S.R.I. mathematical model of electrostatic precipitation which was developed in conjunction with studies of emissions from coal-fired boilers.

Figure 33 shows the experimental fractional efficiency curve representative of the entire test period and two theoretical projections. The input data which were used in the model are given in Table 19. The inlet size distribution is the one which was measured and may lead the model to predict a lower overall mass efficiency than it should. The operating voltages and currents were taken to be representative of those which could be maintained in the precipitator based on measurements made during the test period (average of upper limit of V-I curves measured on 1/12/77). The values for the flow rate and temperature are based on data at the inlet.

In both theoretical projections shown in Figure 33, the normalized standard deviation of the velocity distribution was assumed to be 0.25 and it was assumed that 5% gas sneakage occurred over three stages (actual gas sneakage was much greater than this, however). Losses in efficiency due to rapping reentrainment were determined by a procedure developed for the Electric Power Research Institute based on rap and no-rap studies of precipitators collecting fly ash. The existing model does not account for certain effects such as particle charging near corona wires, particle concentration gradients, and flow field phenomena which should enhance particle collection. Empirical correction factors for the calculated migration velocities have been developed based on comparisons of measured no-rap migration velocities and those based on data from precipitators which were at least 27 feet in electrical length and were collecting fly ash. Thus, the extent of applicability, if any, to the Kennecott precipitator is unknown. Theoretical curve I contains these correction factors whereas curve II does not.

TABLE 19.

COMPUTER DATA INPUT (KENNECOTT)

SCA = 349 ft^2/1000 acfm

Volume Flow - 1.555 x 10^5 acfm (Inlet)
Inlet Grain Loading - 0.20 gr/acf
Total Collecting Length - 22.5 ft
Gas Velocity - 2.59 ft/sec
Estimated Efficiency - 95.0%
Dust Density - 3130 kg/m^3
Resistivity - 1.9 x 10^{10} ohm-cm
Gas Temperature - 473°F
Atmospheric Pressure - 710 mm of Hg
No. of Electrical Fields - 3

Field No.	1	2	3
Length of Electrical Field (ft)	7.5	7.5	7.5
Area of Electrical Field (ft^2)	18,100	18,100	18,100
Average Applied Voltage (kV)	52.0	44.1	46.1
Average Current (A)	0.158	0.425	0.489
No. of Wires/Linear Section	12	12	12
1/2 Wire-to-Wire Spacing (in)	3.0	3.0	3.0
Total Wire Length (ft)	13,215	13,215	13,215
Corona Wire Radius (in)	0.078125	0.078125	0.078125
Wire-to-Plate Spacing (in)	5.0	5.0	5.0

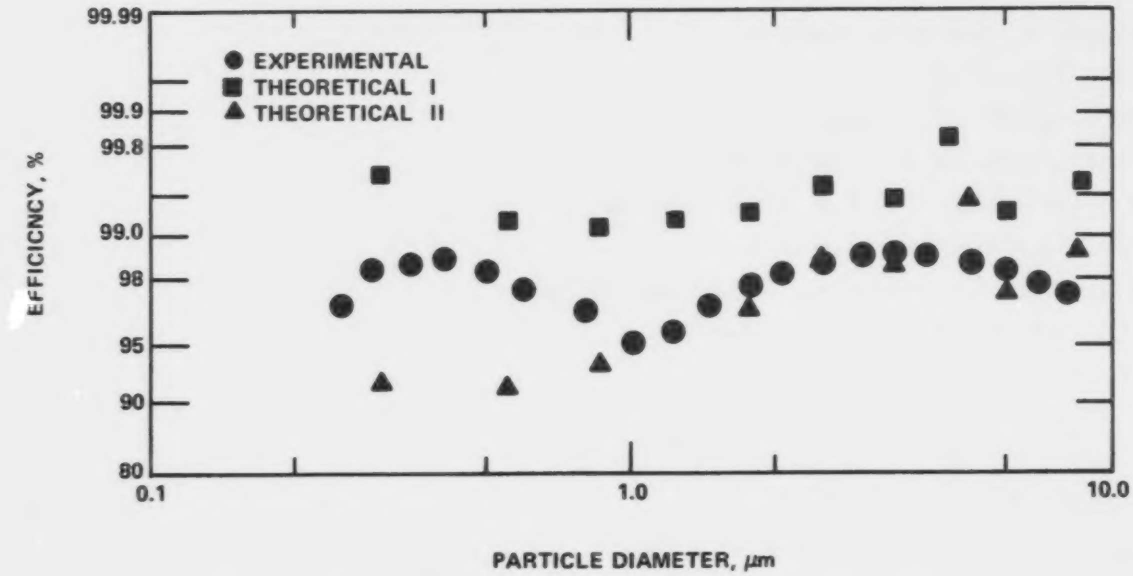


Figure 33. Theoretical and experimental fractional efficiencies.

APPENDIX A

SMELTER OPERATING CHARTS

This Appendix contains photocopies of instrument charts indicative of the smelter operating conditions during the test period. The charts give the twenty four hour operating data for the reactor feed rate and the reactor and reverberatory furnace temperatures. In addition, example charts for the reverberatory furnace typical flow rate, reactor air flow rate, and waste heat boiler profile are presented.

Operation	Date	Page
Reactor (Roaster) Feed Rate	Jan 11	92
	12	93
	13	94
	14	95
	15	96
	16	97
Reactor (Roaster) Temperature	11	98
	12	99
	13	100
	14	101
	15	102
	16	103
Reverberatory Furnace Temperature	11	104
	12	105
	13	106
	14	107
	15	108
	16	109
Typical Reverberatory Gas Flow Chart	-	110
Typical Reactor (Roaster) Air Flow Chart	-	111
Typical Waste-Heat Boiler Profile	-	112

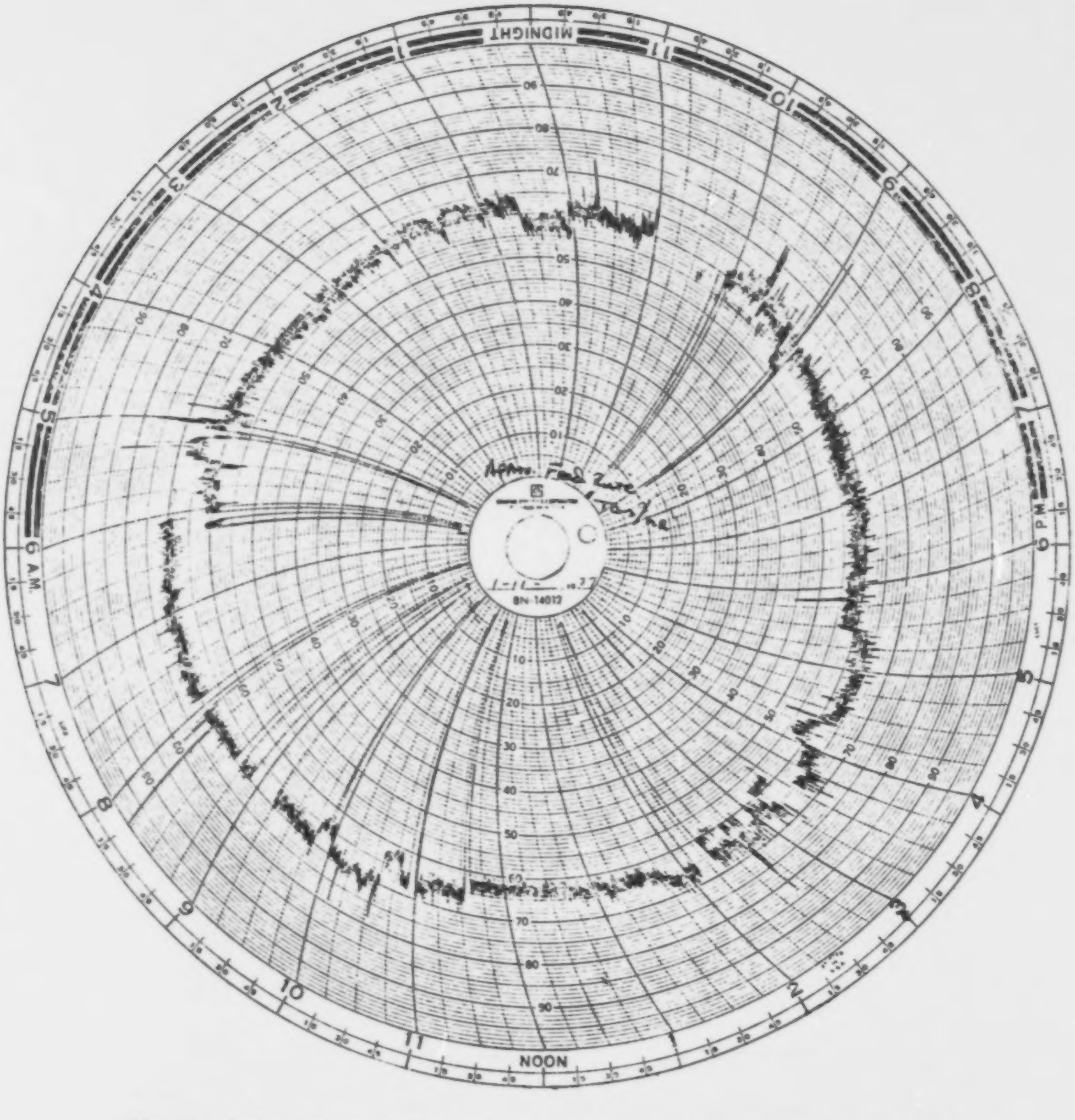


Figure A-1: Approximate Reactor (Roaster) Feed Rate, Tons/hr (January 11, 1977)

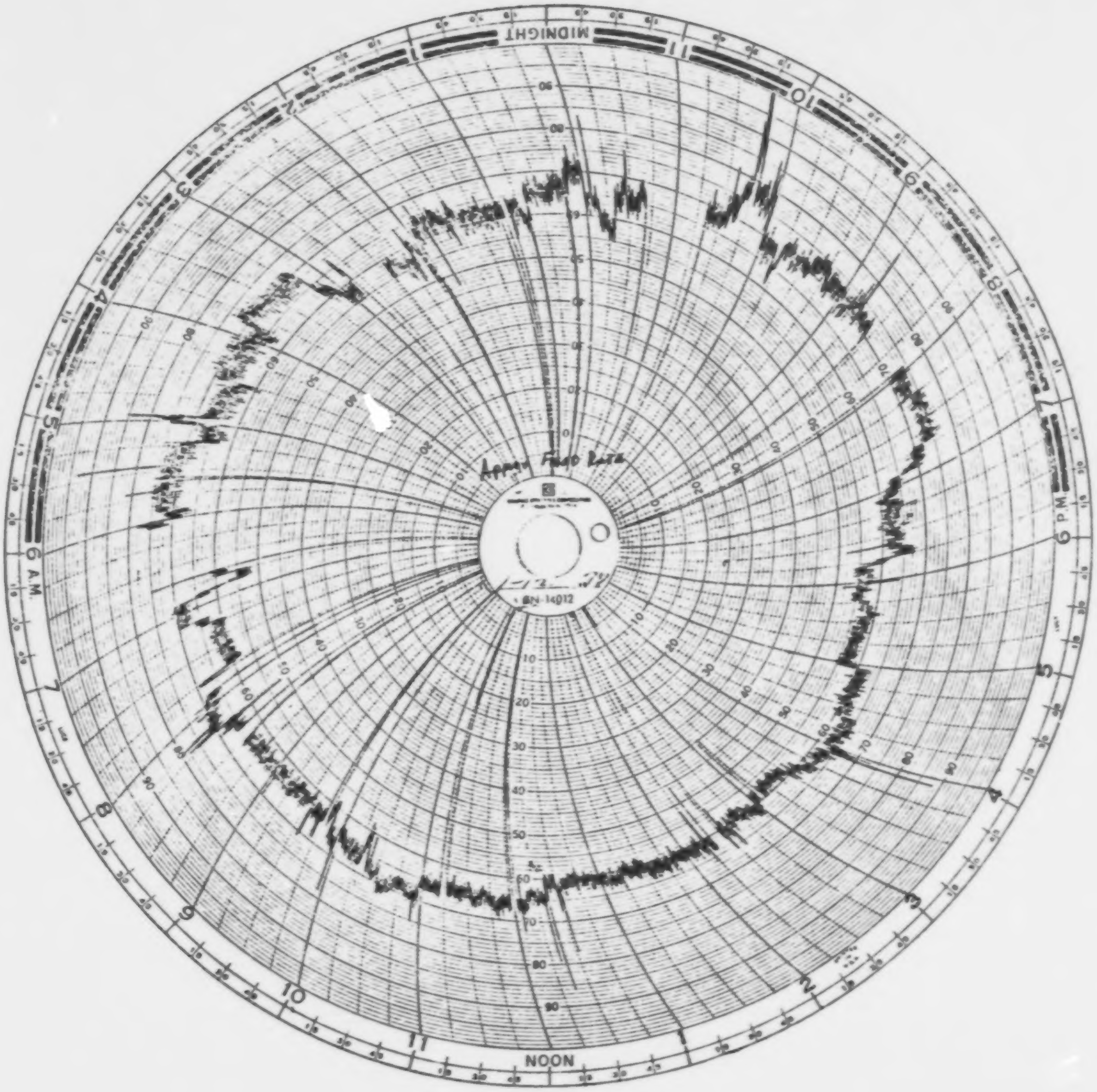


Figure A-2: Approximate Reactor (Roaster) Feed Rate, Tons/hr (January 12, 1977)

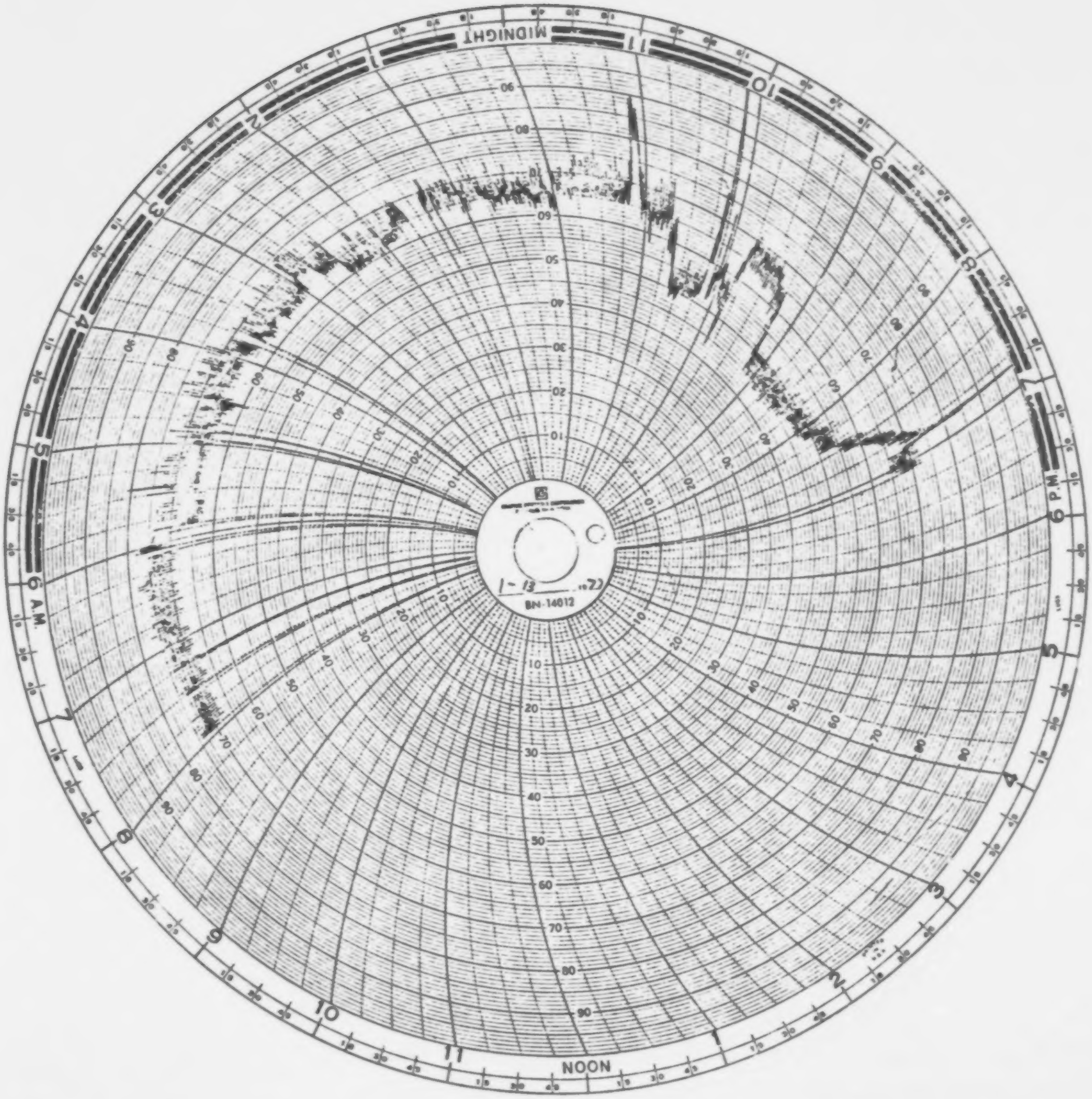


Figure A-3: Approximate Reactor (Roaster) Feed Rate, Tons/hr
(Janaury 13, 1977)

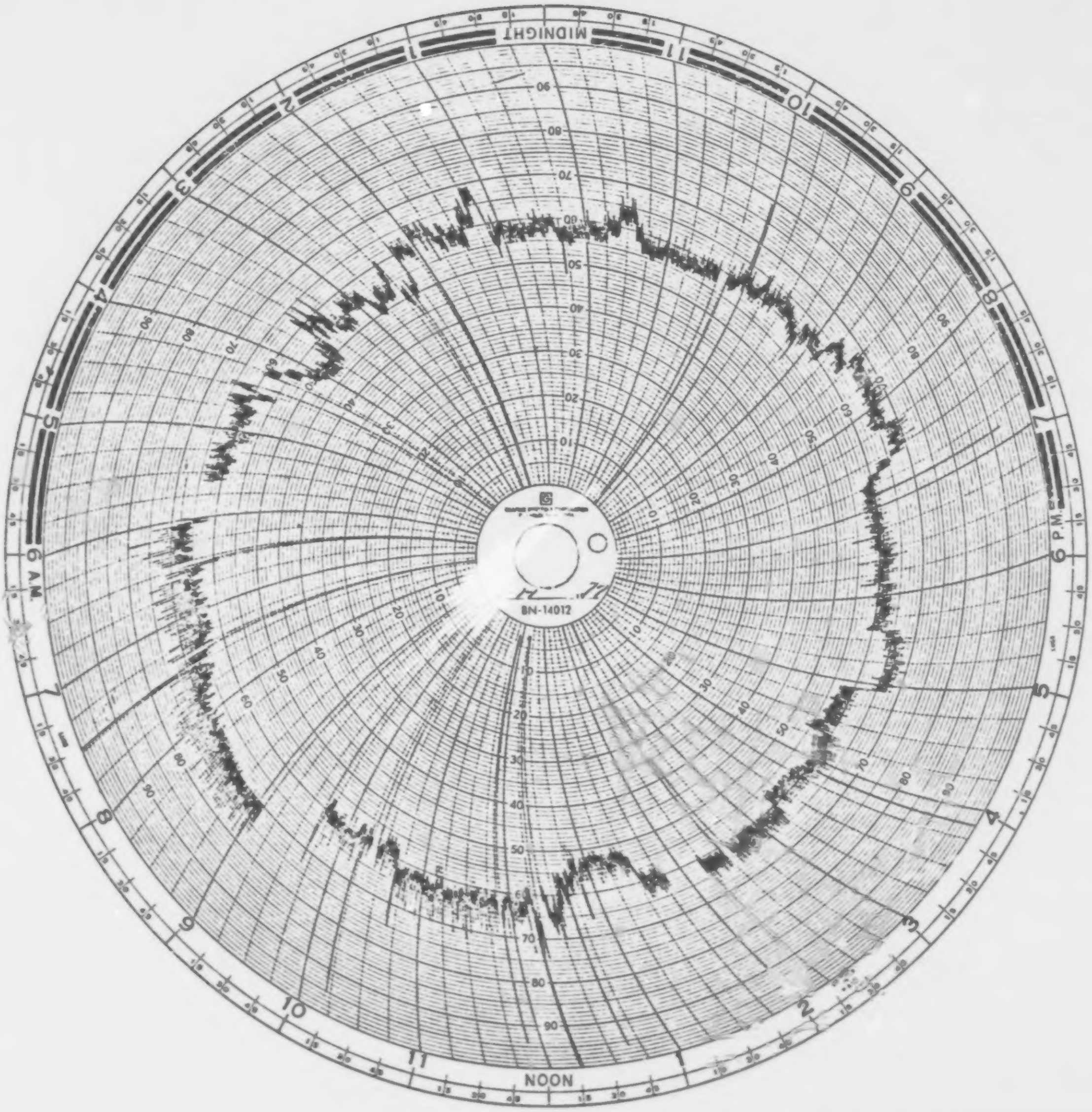


Figure A-4: Approximate Reactor (Roaster) Feed Rate, Tons/hr
(January 14, 1977)

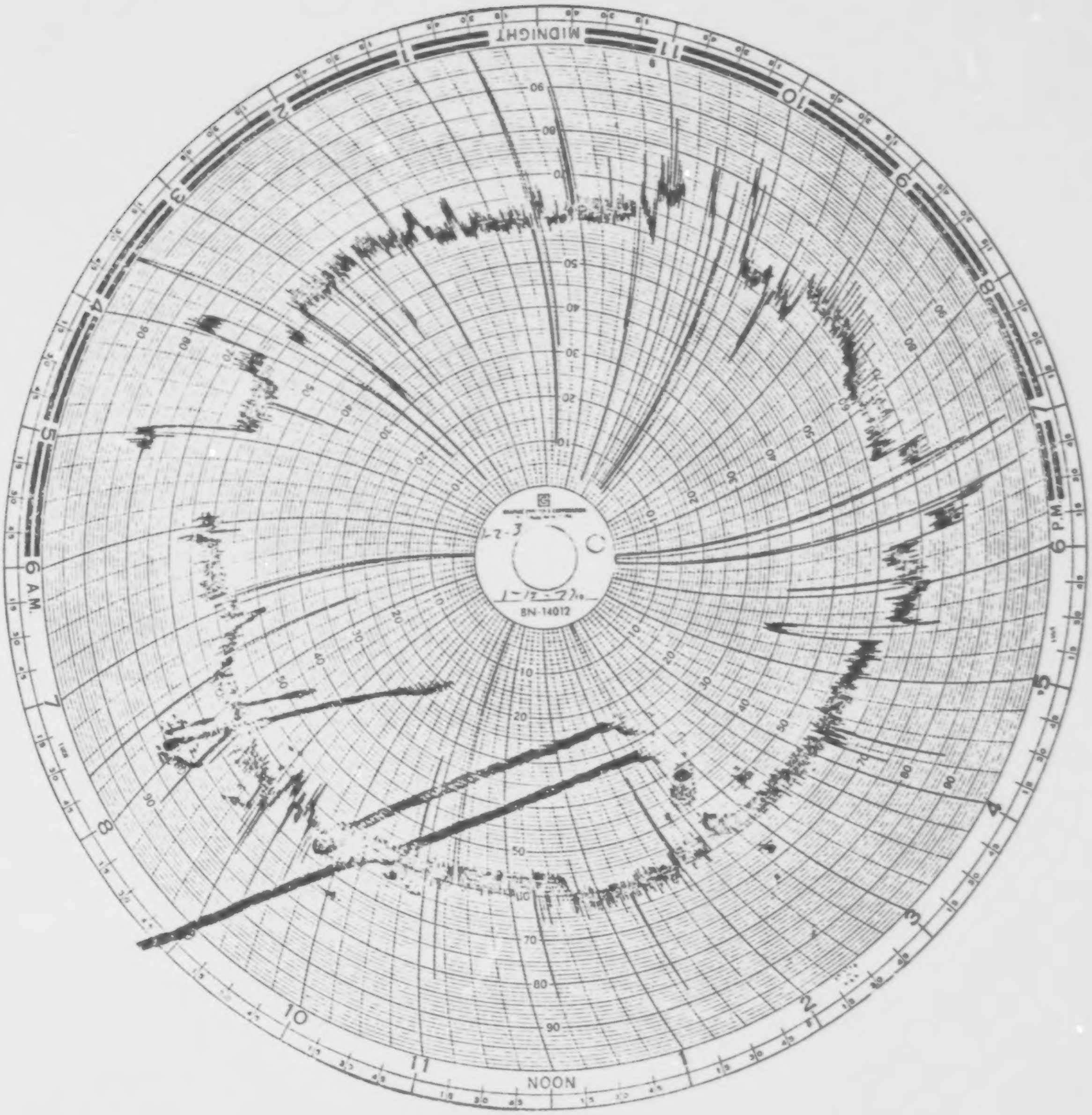


Figure A-5: Approximate Reactor (Roaster) Feed Rate, Tons/hr
(January 15, 1977)

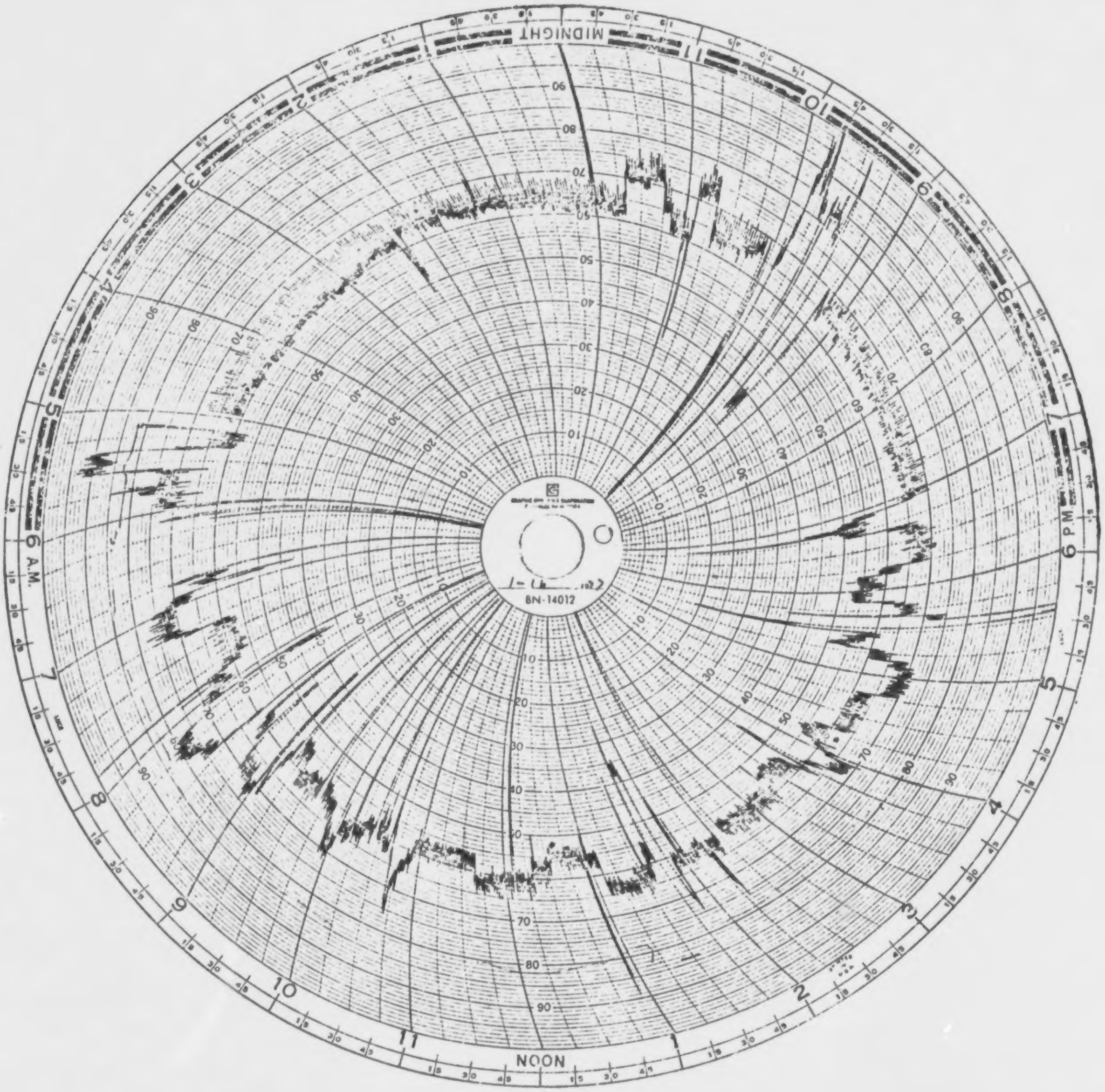


Figure A-6: Approximate Reactor (Roaster) Feed Rate, Tons/hr
(January 16, 1977)

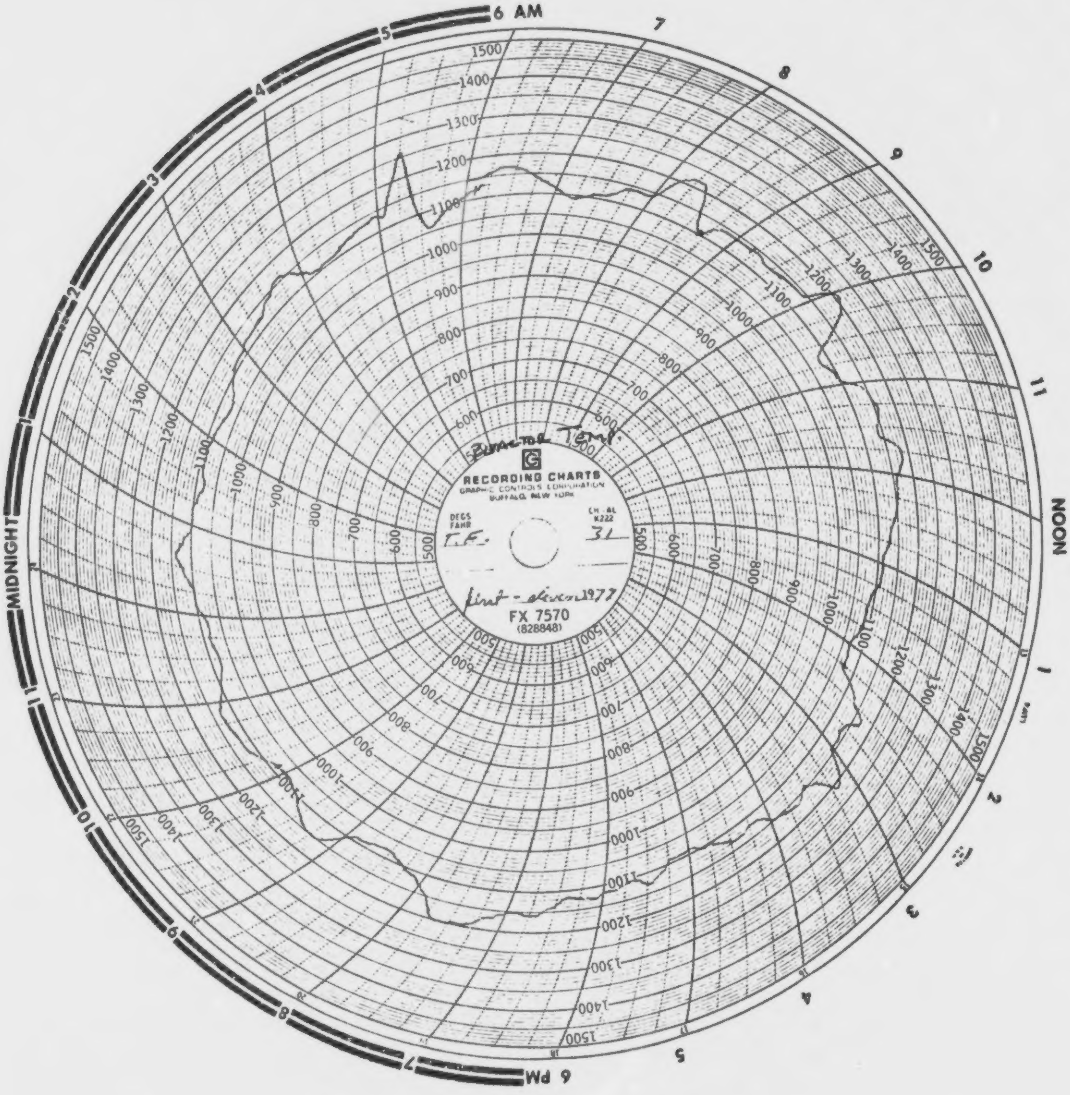


Figure A-7: Reactor (Roaster) Temperature, °F
(January 11, 1977)

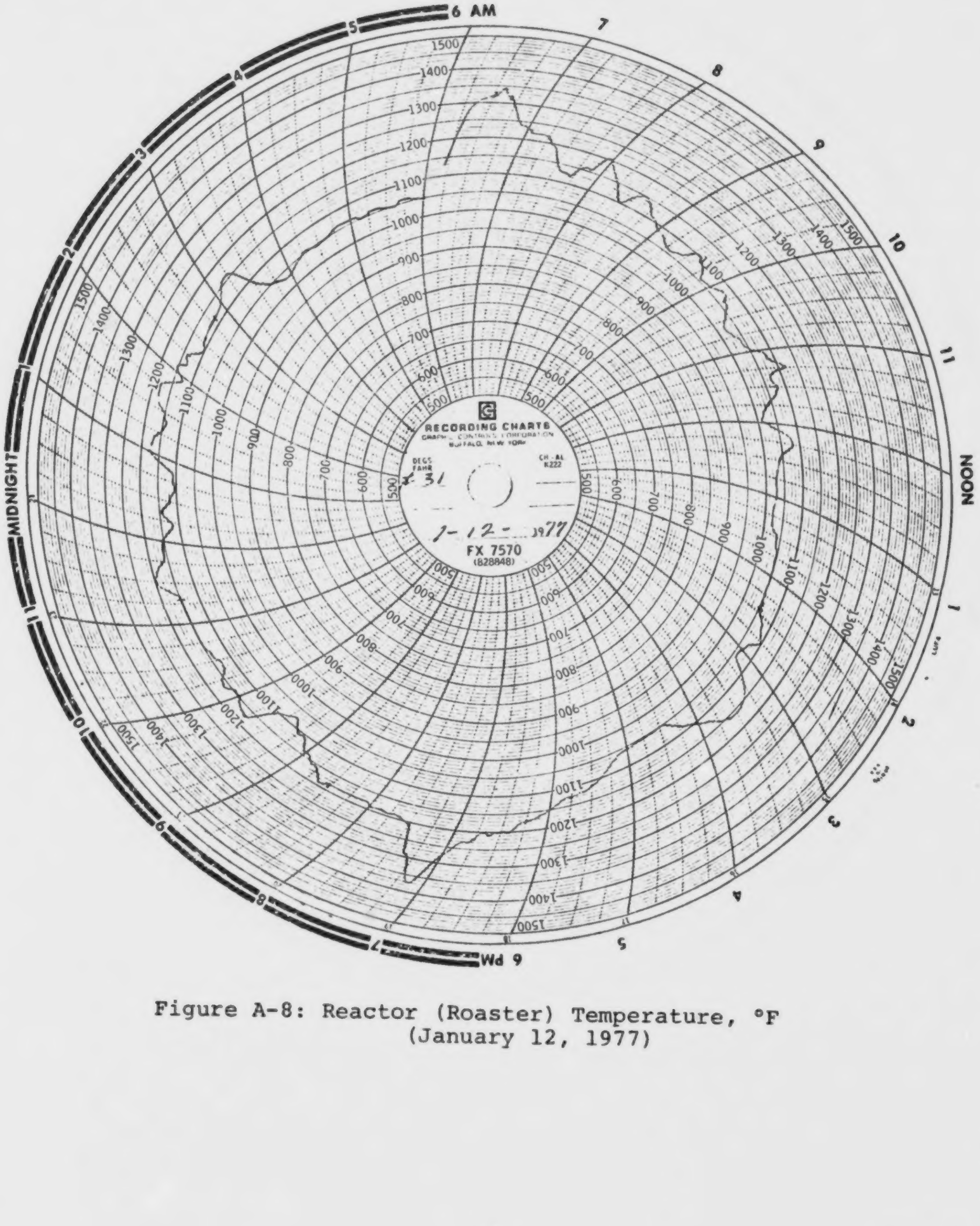


Figure A-8: Reactor (Roaster) Temperature, °F (January 12, 1977)

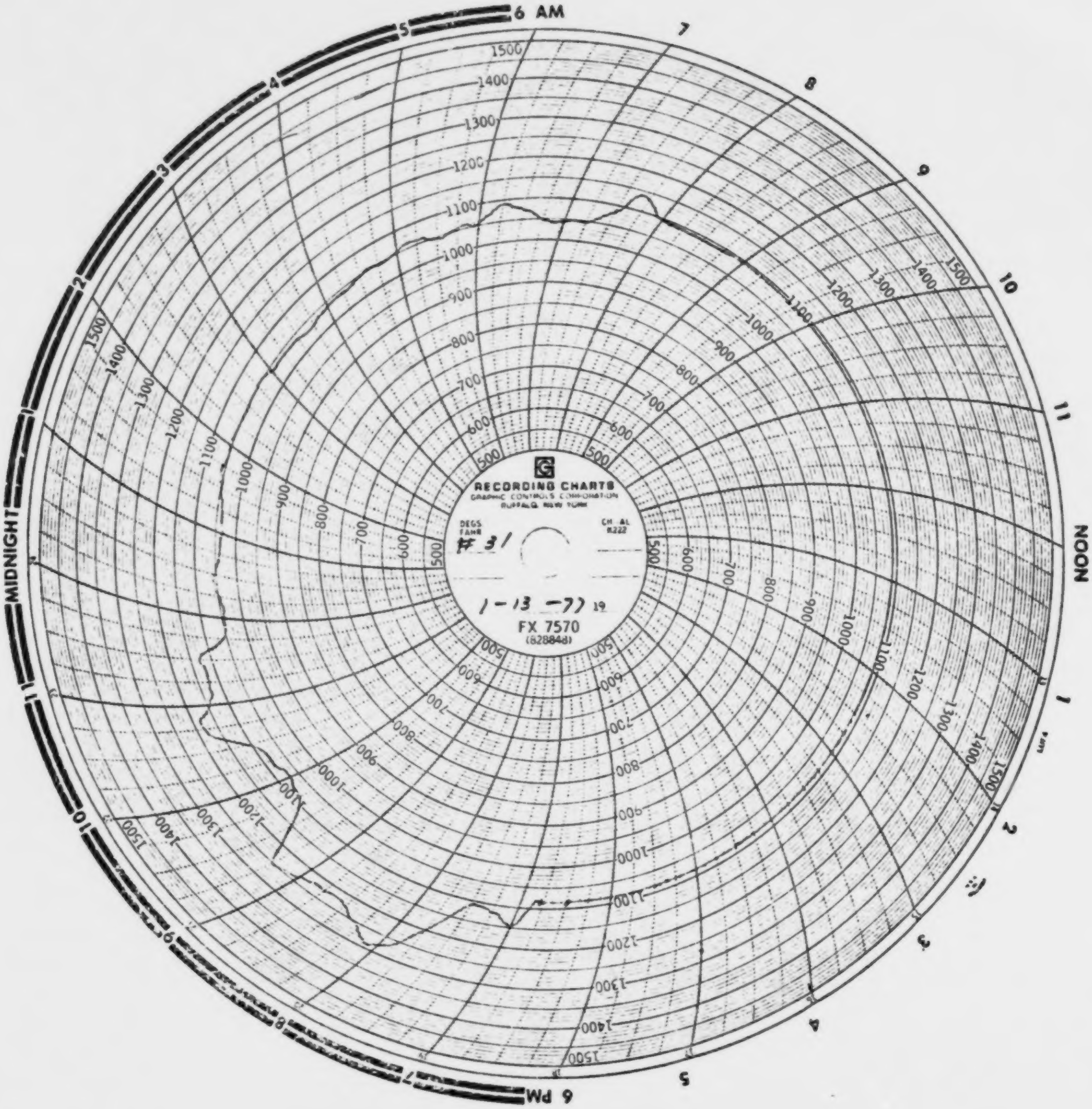


Figure A-9: Reactor (Roaster) Temperature, °F
(January 13, 1977)

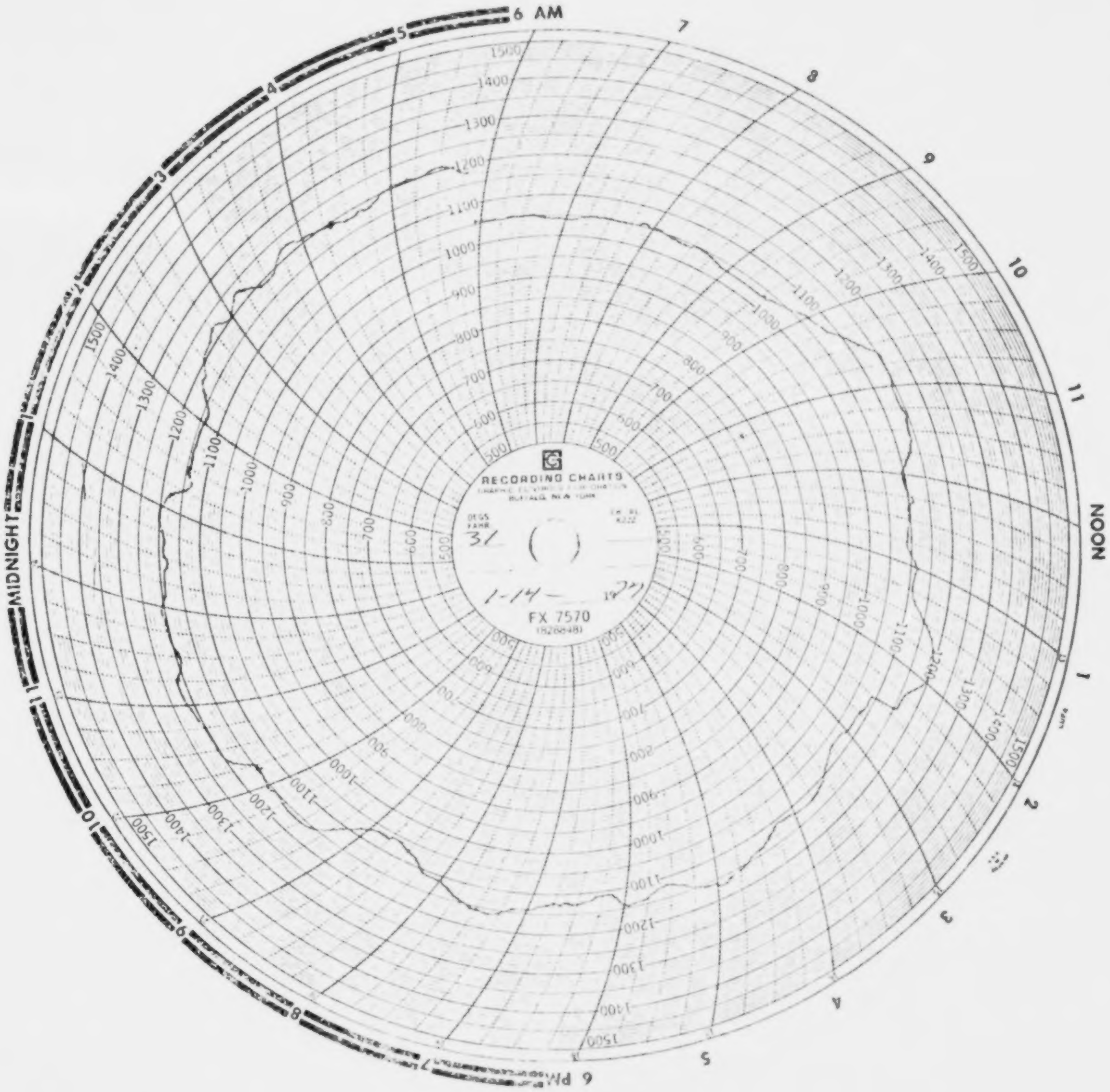


Figure A-10: Reactor (Roaster) Temperature, °F
(January 14, 1977)

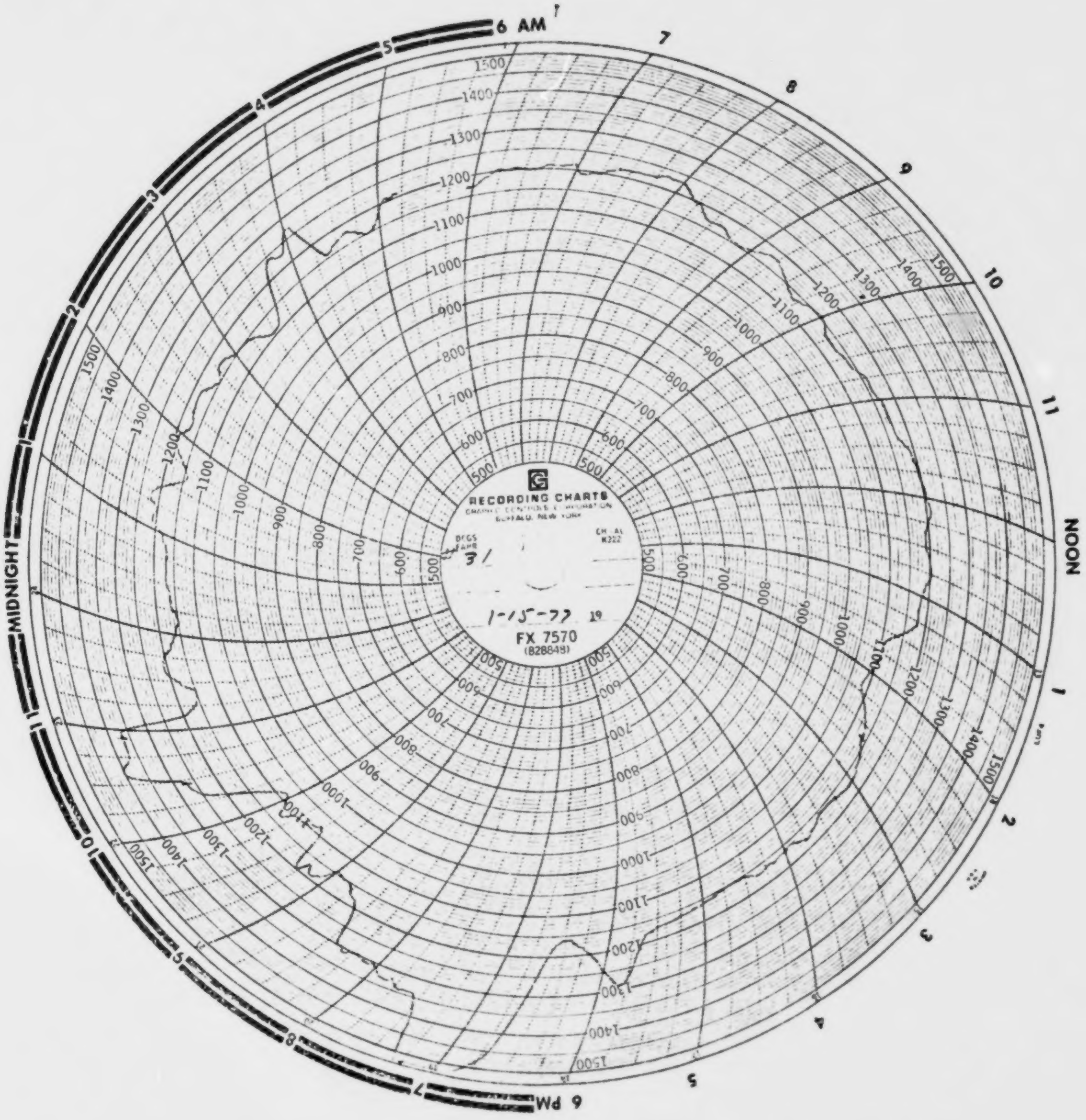


Figure A-11: Reactor (Roaster) Temperature, °F
(January 15, 1977)

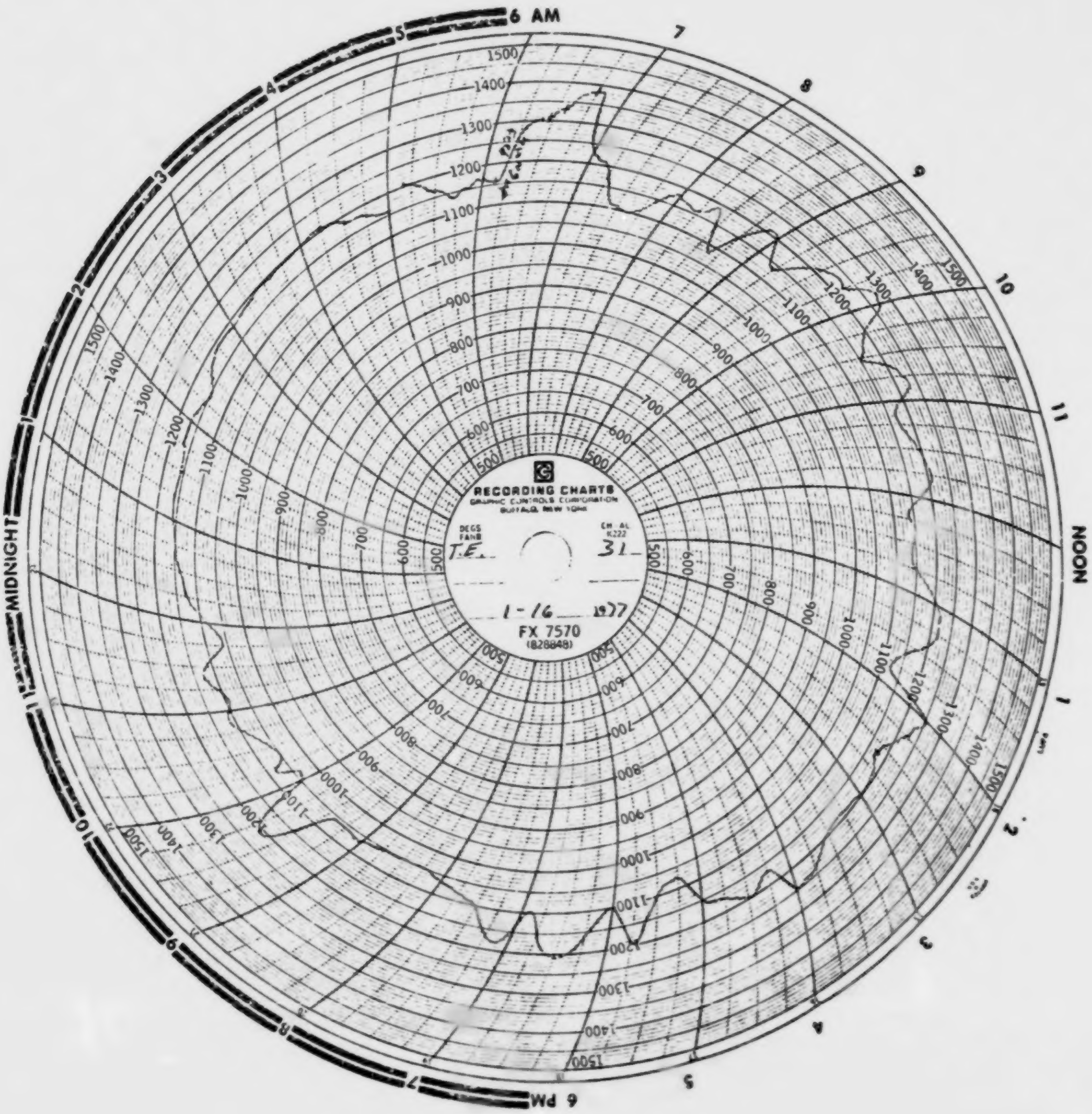


Figure A-12: Reactor (Roaster) Temperature, °F
(January 16, 1977)

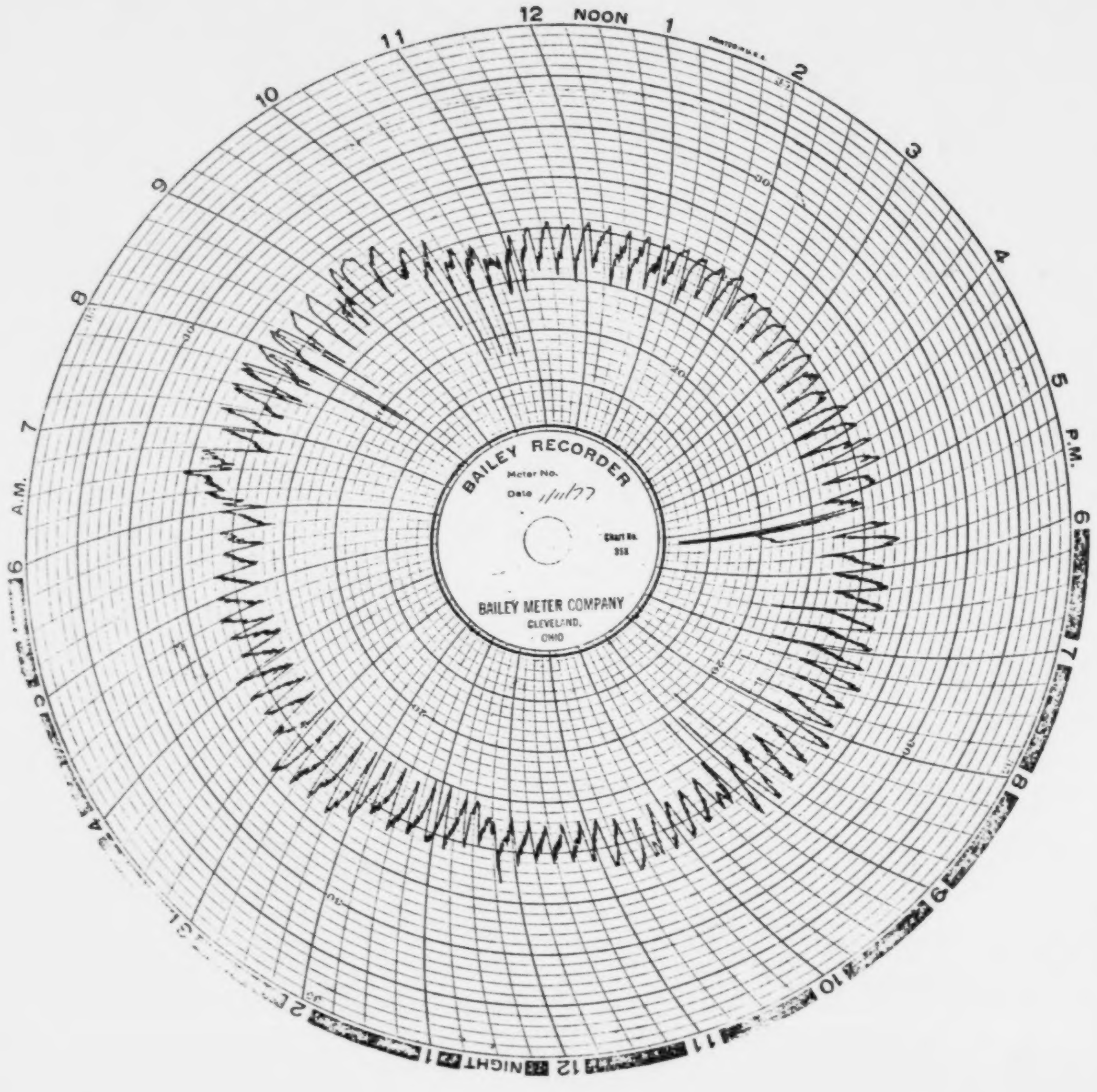


Figure A-13: Reverberatory Furnace Temperature, °F
(January 11, 1977)

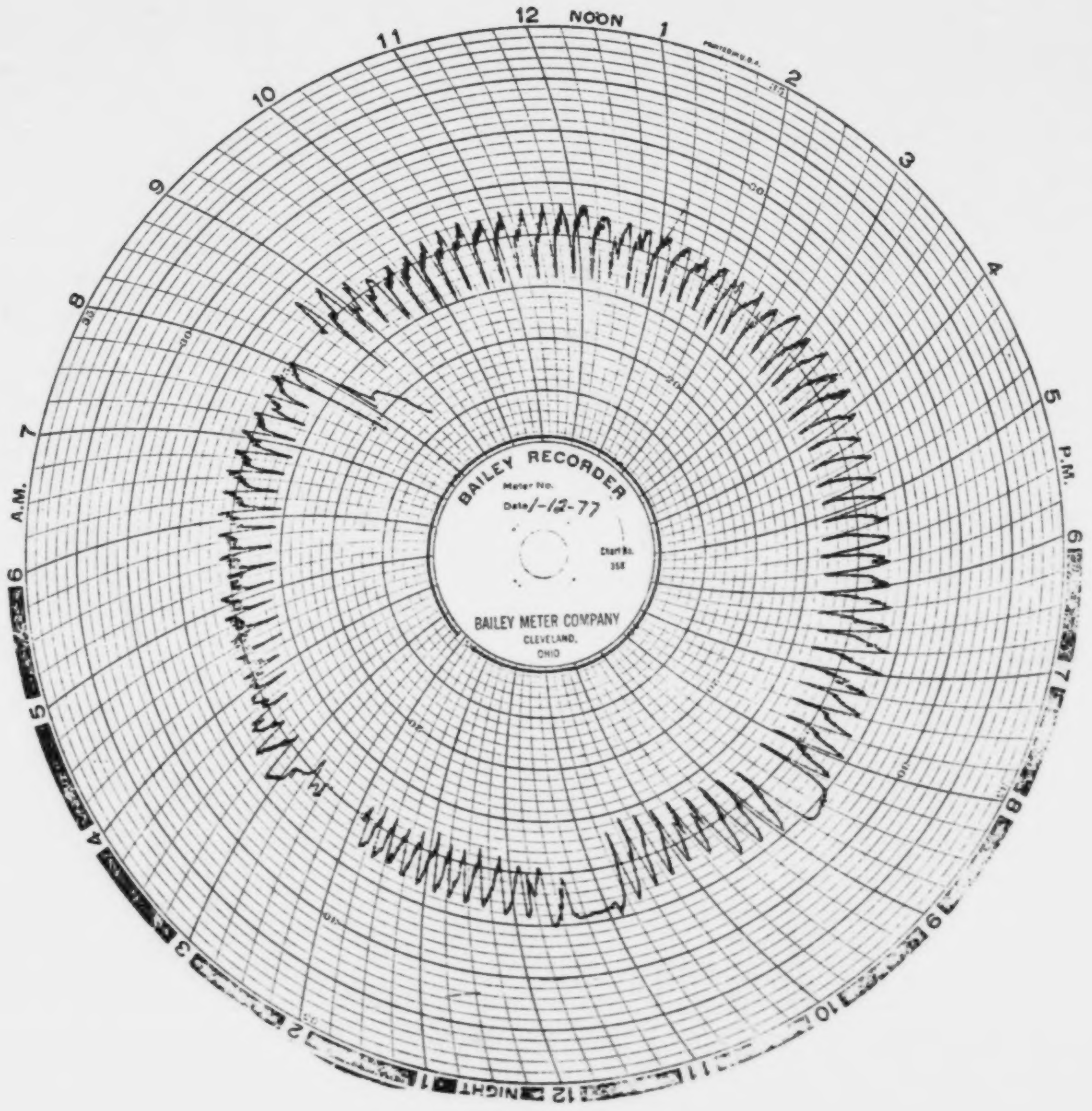


Figure A-14: Reverberatory Furnace Temperature, °F
(January 12, 1977)

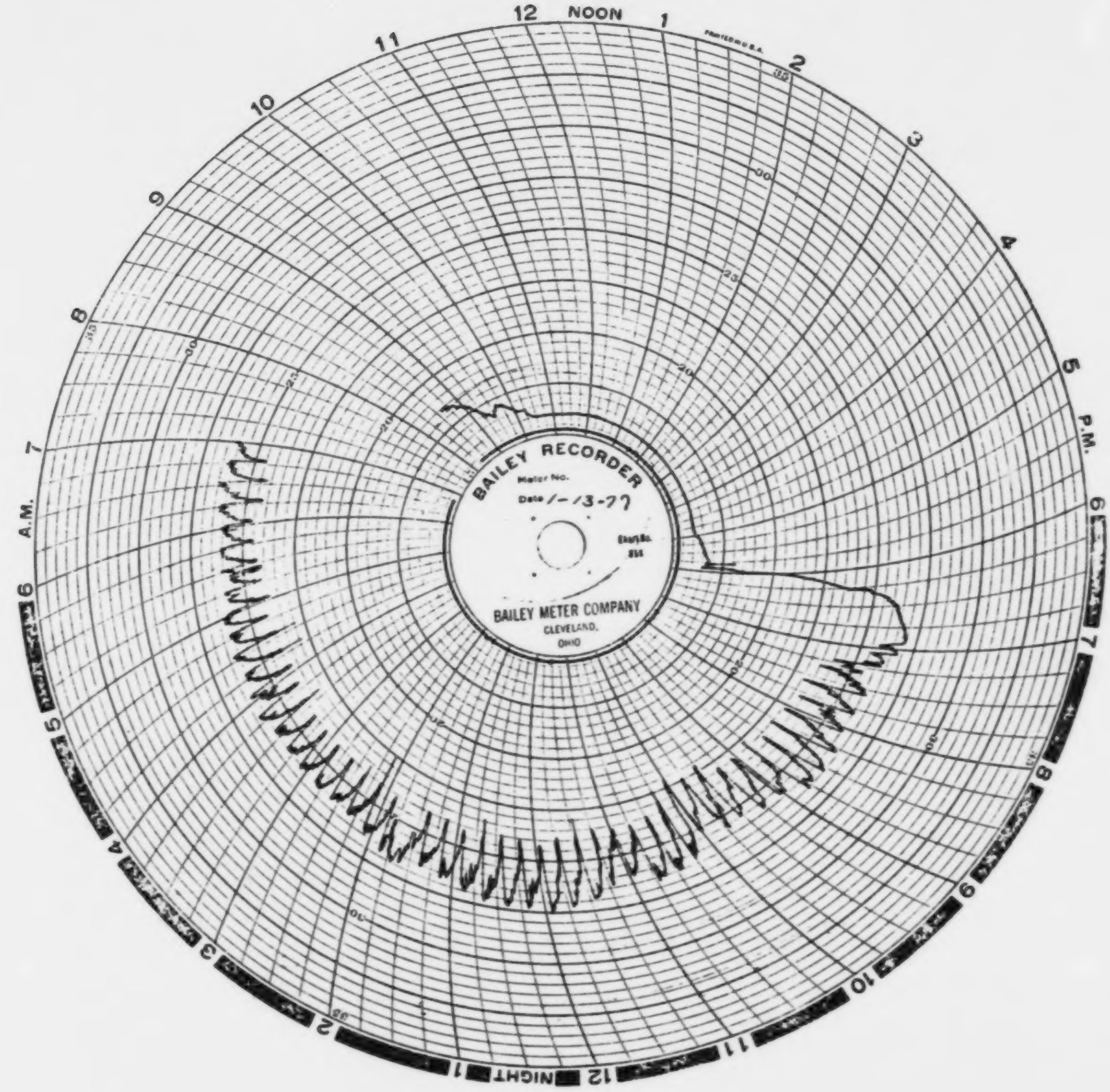


Figure A-15: Reverberatory Furnace Temperature, °F
(January 13, 1977)

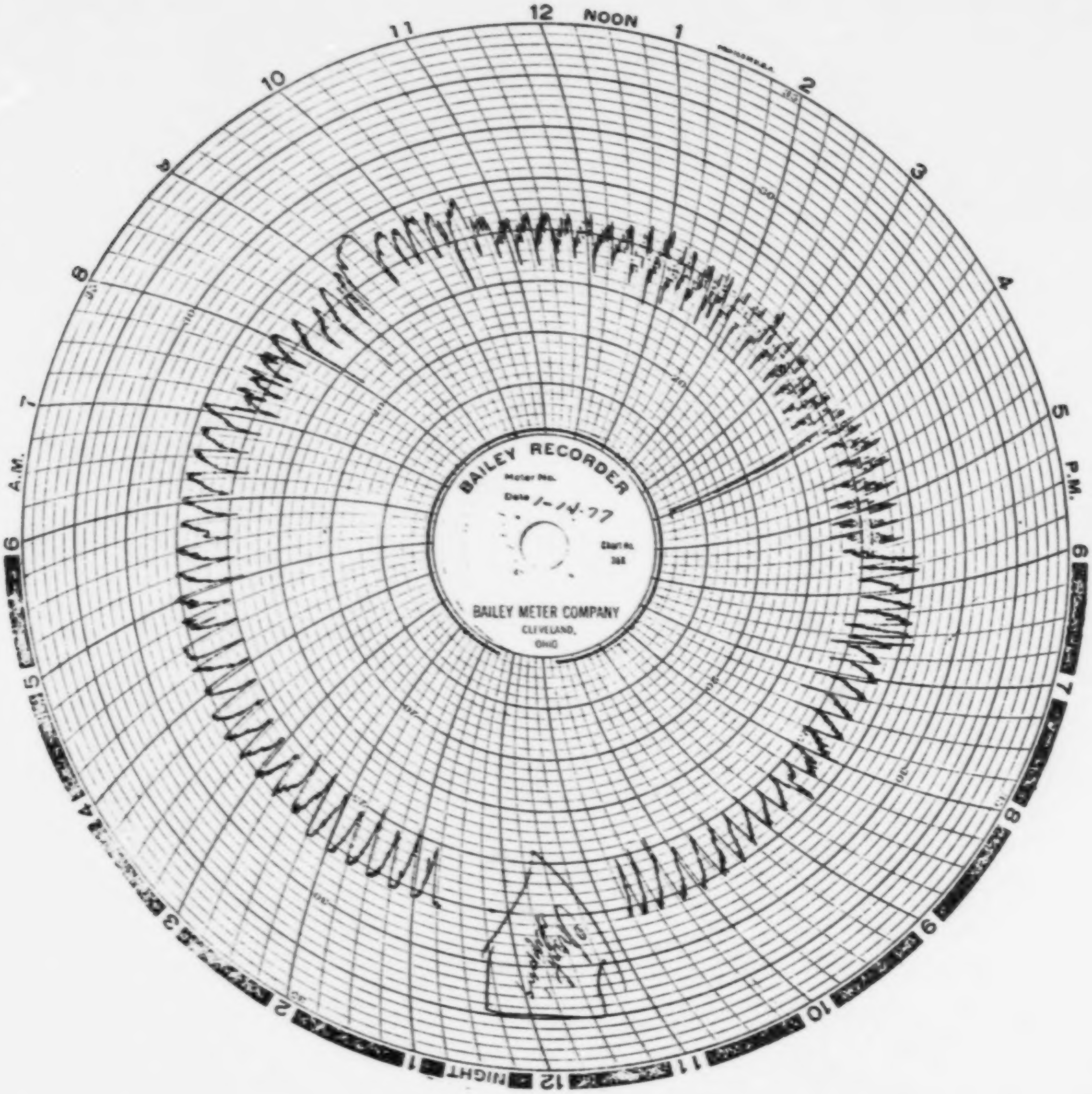


Figure A-16: Reverberatory Furnace Temperature, °F
(January 14, 1977)

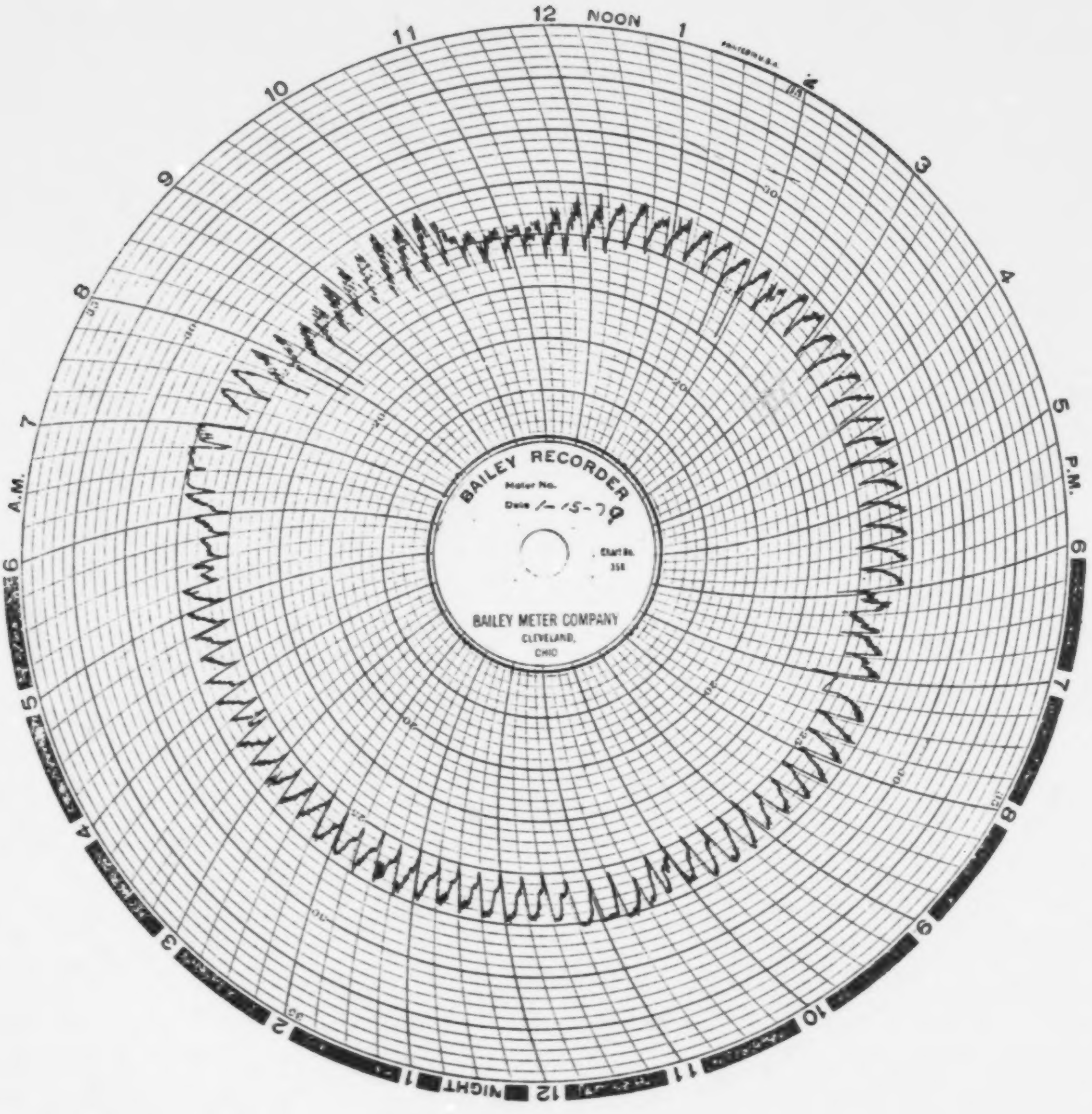


Figure A-17: Reverberatory Furnace Temperature, °F
(January 15, 1977)

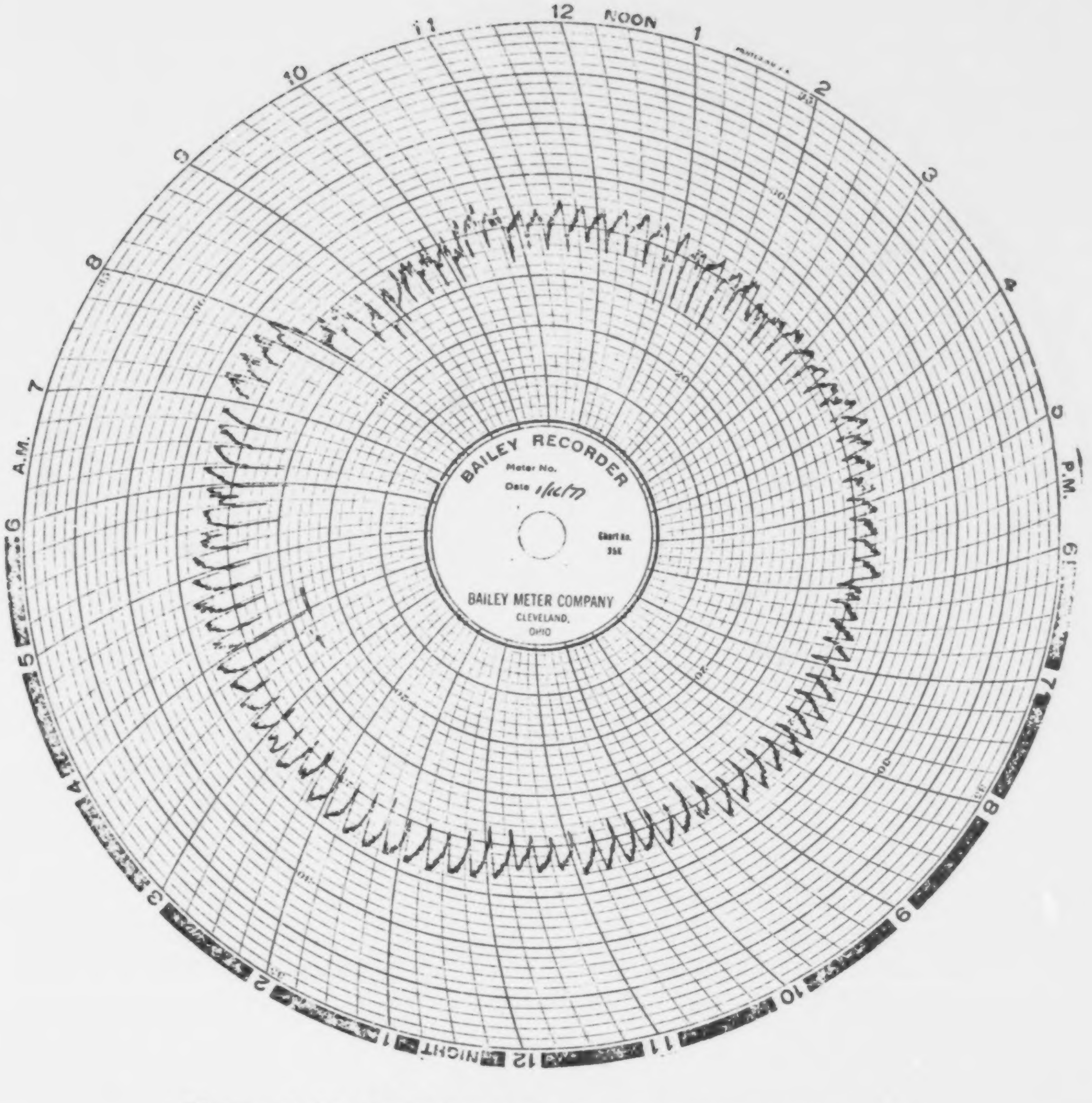


Figure A-18: Reverberatory Furnace Temperature, °F
(January 16, 1977)

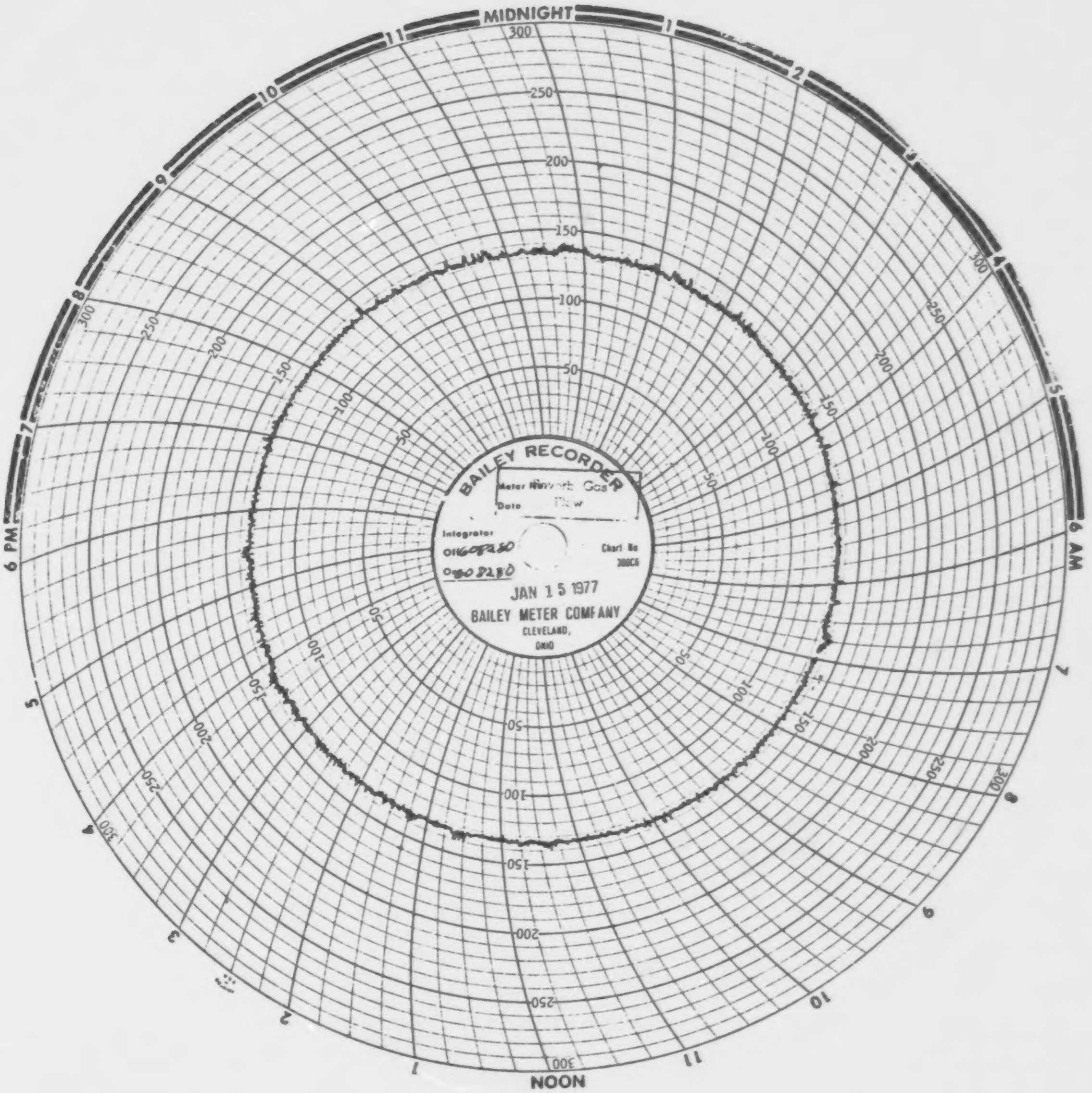


Figure A-19: Typical Reverberatory Gas Flow Chart
(Not Calibrated)

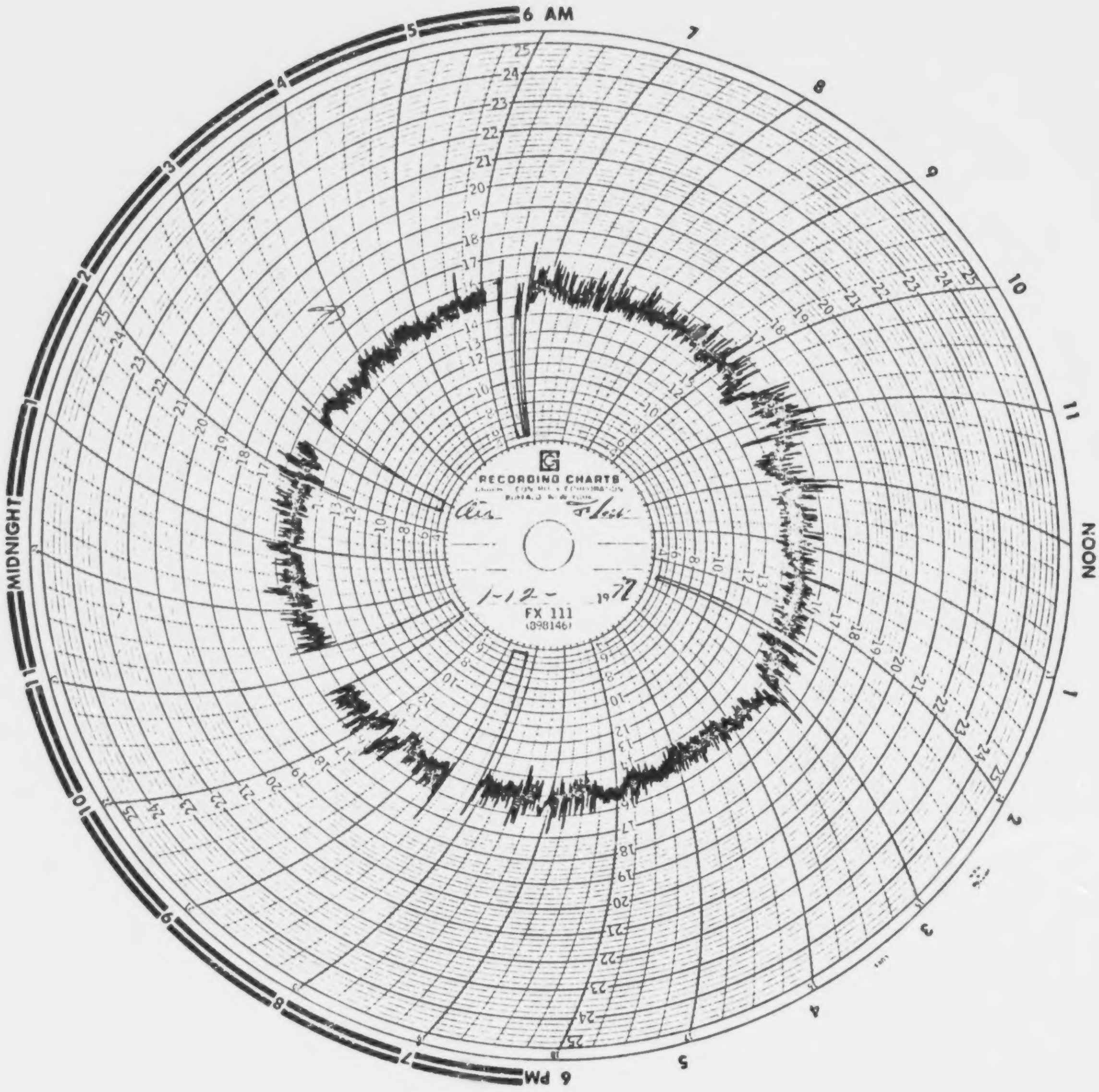


Figure A-20: Typical Reactor (Roaster) Air Flow Chart

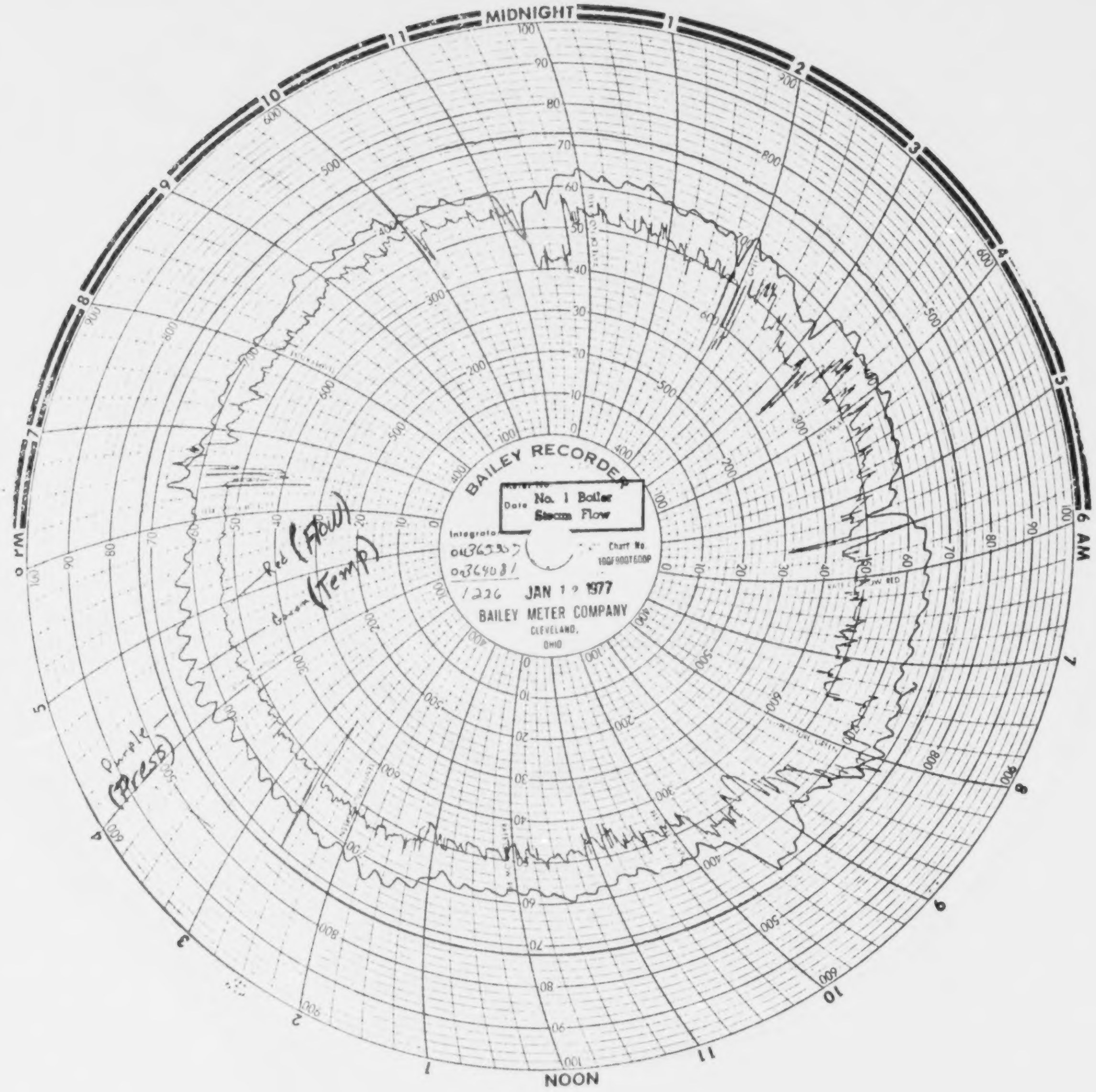


Figure A-21: Typical Waste-Heat Boiler Profile

APPENDIX B

CHEMICAL SAMPLING AND ANALYSIS BY RADIAN CORPORATION

SAMPLING TRAINS

Trace Elements: Gaseous and Particulate

The samples for analysis of elements in gaseous compounds and particulates were collected from the reverberatory off-gases at the ESP inlet and outlet and at the stack. The samples were collected isokinetically from single points in the ESP inlet and outlet ducts. The stack was sampled isokinetically over a 10 point traverse along one diameter.

The train used is shown in Figure B-1. Samples were drawn through a Pyrex sampling nozzle and probe and then through a wet electrostatic precipitator (WEP) by means of Teflon tubing. In the WEP, shown in greater detail in Figure B-2, gas bubbled through the circulating electrolytic reservoir and then passed up through a cylindrical chamber, the walls of which were wetted with the electrolyte (5% nitric acid). Collection of particulate and vapors was achieved in this area by applying a 12-kV potential across the center platinum electrode and the wetted outer wall, thus creating a corona discharge at the platinum wire. The particulate-free gas stream exited at the top of the WEP. The sample was retained in the electrolyte as a mixture of suspended solids and dissolved species.

Gaseous compounds escaping the WEP were collected by a series of eight impingers. The contents of each impinger is given in Table B-1.

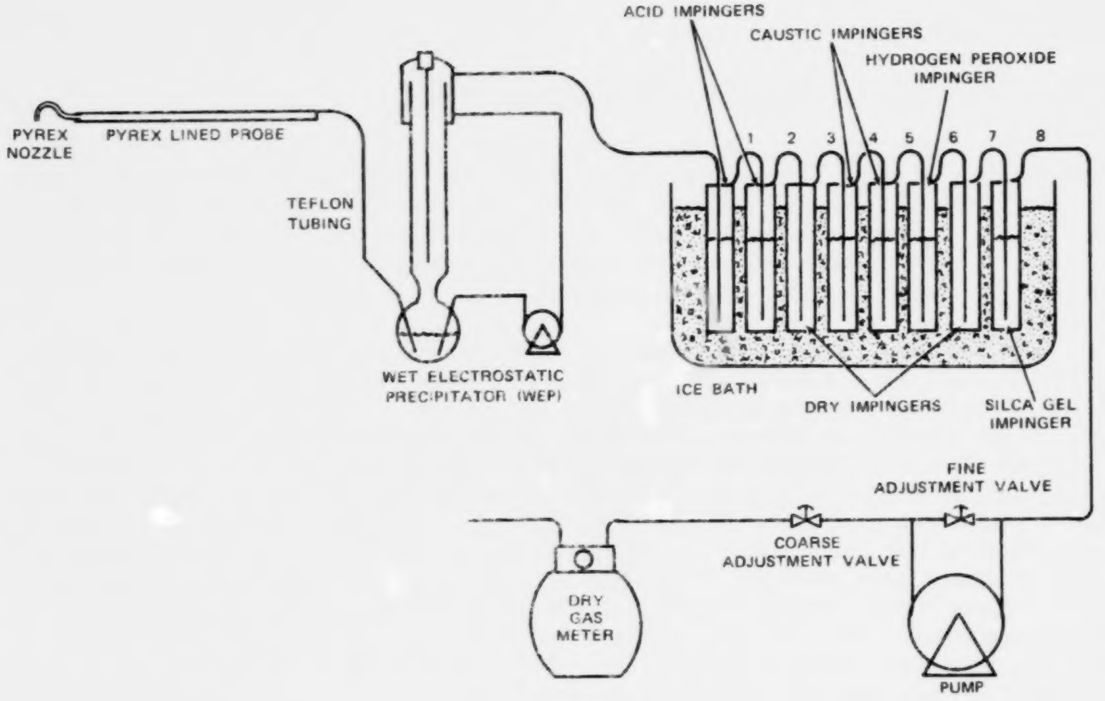


Figure B-1. Schematic diagram of the Integral WEP Sampling Train.

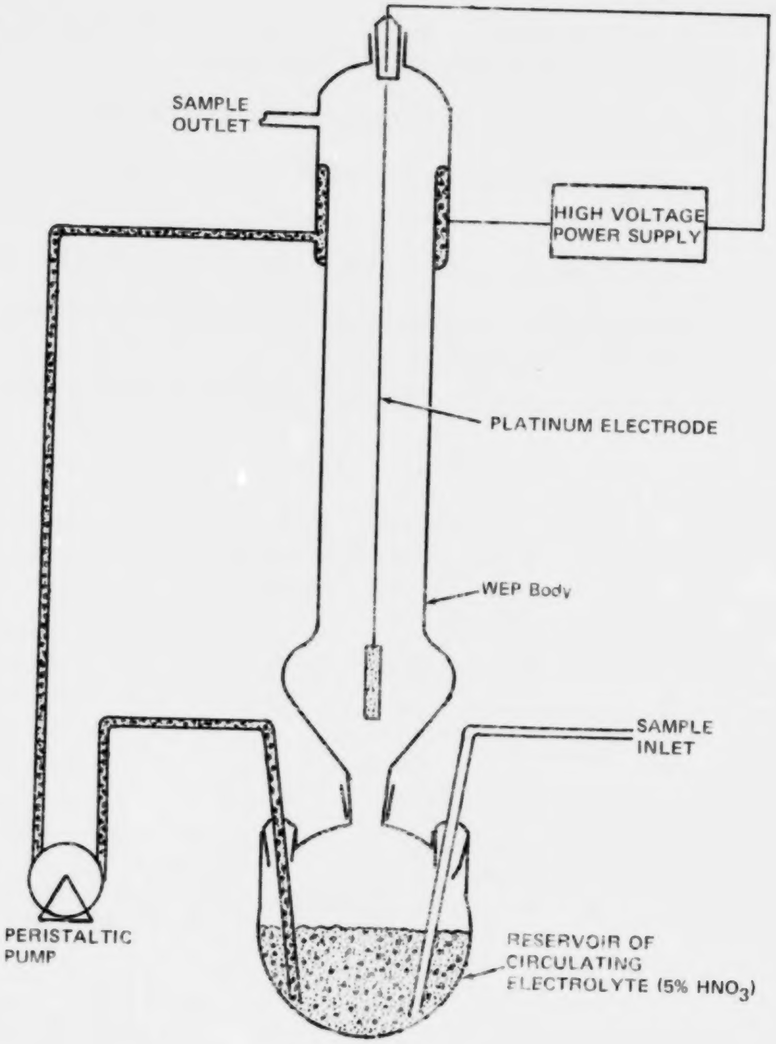

SAMPLE OUTLET
HIGH VOLTAGE POWER SUPPLY
PLATINUM ELECTRODE
WEP Body
SAMPLE INLET
PERISTALTIC PUMP
RESERVOIR OF CIRCULATING ELECTROLYTE (5% HNO$_3$)

Figure B-2. Wet Electrostatic Precipitator.

TABLE B-1. IMPINGER SOLUTIONS USED FOR TRACE ELEMENT COLLECTION

Impinger Number	Solutions
1,2	1:1:1 sulfuric acid, nitric acid, deionized water in a Greenburg-Smith impinger
3,7	dry modified Greenburg-Smith impingers
4,5	20% potassium hydroxide in a Greenburg-Smith impinger
6	hydrogen peroxide in a Greenburg-Smith impinger
8	preweighed silica gel in a modified Greenburg-Smith impinger

Mercury Vapor

Mercury vapor was collected by a gold amalgamation technique. The gas was first passed through an in-stack glass-fiber filter to remove particulates, then through 6% hydrogen peroxide to remove SO_2 interference, and finally through a quartz tube containing a plug of very fine gold wire. Mercury vapor was collected on the gold surface through amalgamation. The mercury was later thermally desorbed and analyzed with a flameless atomic absorption technique.

Vapors of Other Trace Elements

The collection of compounds in the vapor state was accomplished with a series of impingers preceded by a glass-fiber in-stack filter to remove particulates. The sampling train is shown in Figure B-3. The contents of the impingers were identical to those listed in Table B-1.

Sampling Schedule

The schedule of sampling with the WEP train and the vapor train is given in Table B-2. In general, sampling with the mercury vapor train was performed as part of each operation with the WEP train or the vapor train.

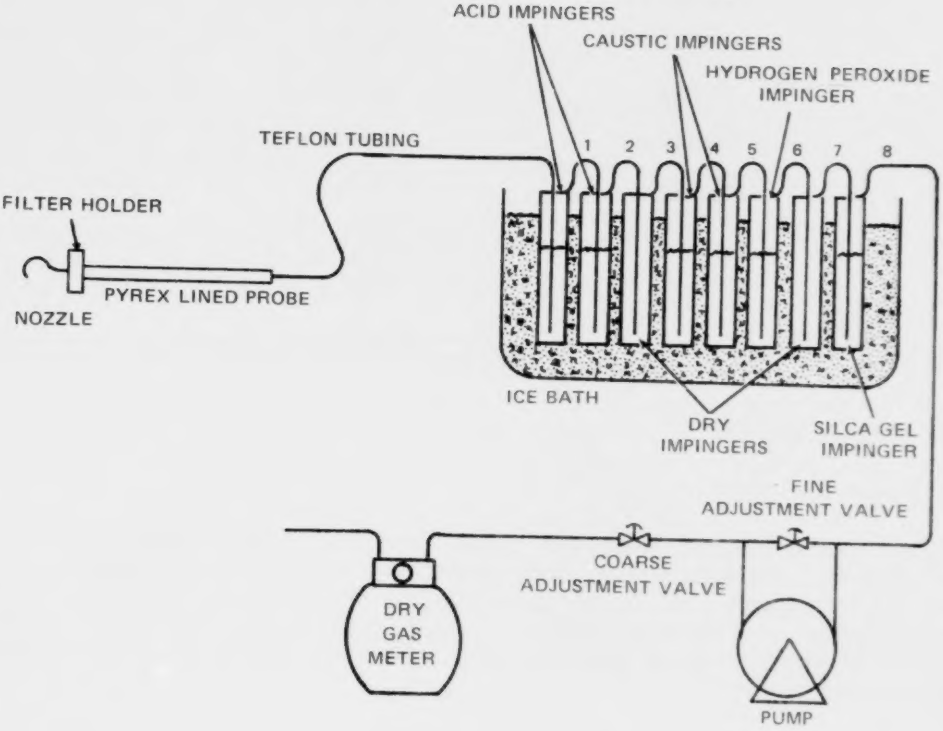


Figure B-3. Schematic diagram of the Vapor-Phase Element Sampling Train.

TABLE B-2. SCHEDULE OF SAMPLING
BY RADIAN CORPORATION

Date	Location	Train	Time, hr
Jan. 11	Outlet	Vapor	1120 - 1630
Jan. 12	Inlet	WEP	1128 - 1613
	Outlet	WEP	1052 - 1730
	Outlet	Vapor	0917 - 1705
Jan. 14	Inlet	WEP	0843 - 1500
	Outlet	Vapor	0917 - 1705
	Stack	WEP	0950 - 1630
Jan. 15	Inlet	WEP	0943 - 1343
	Stack	WEP	0940 - 1625

ANALYTICAL METHODS

Trace Elements

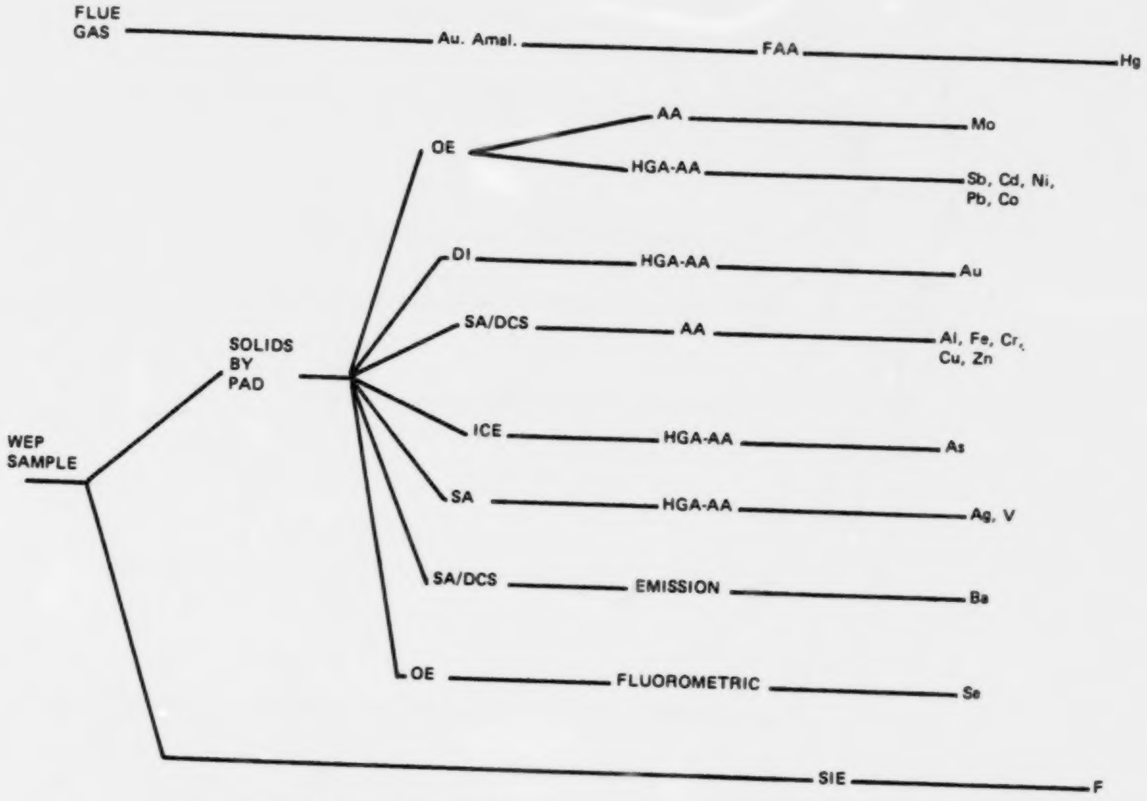
The analysis of samples from the WEP train consisted of two major steps: dissolution and chemical analysis. Sample dissolution techniques included perchloric acid digestion and lithium borate fusion. The analytical techniques were based on atomic absorption spectrophotometry (AAS), ion-selective electrometry, and fluorometry.

Figures B-4, B-5, and B-6 summarize the dissolution and analytical procedures. The remainder of this section describes the procedures in greater detail.

Sample Dissolution

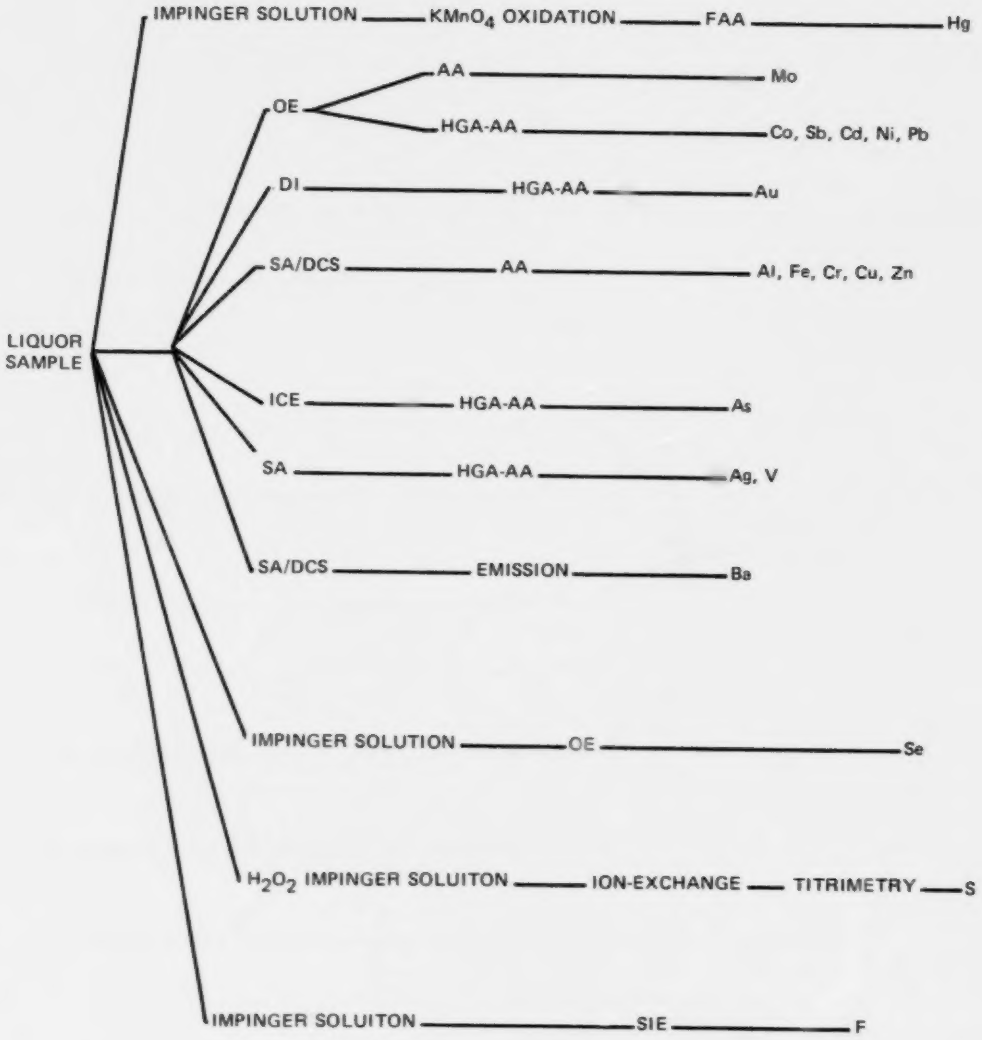
The dissolution of solid samples (from the WEP train or the ESP hoppers) was achieved with the following techniques:

- Percholoric acid digestion - The sample was first treated with nitric and hydrofluoric acids. Perchloric acid was added for final oxidation of the sample. A small amount of hydrochloric acid was finally added to ensure complete dissolution.



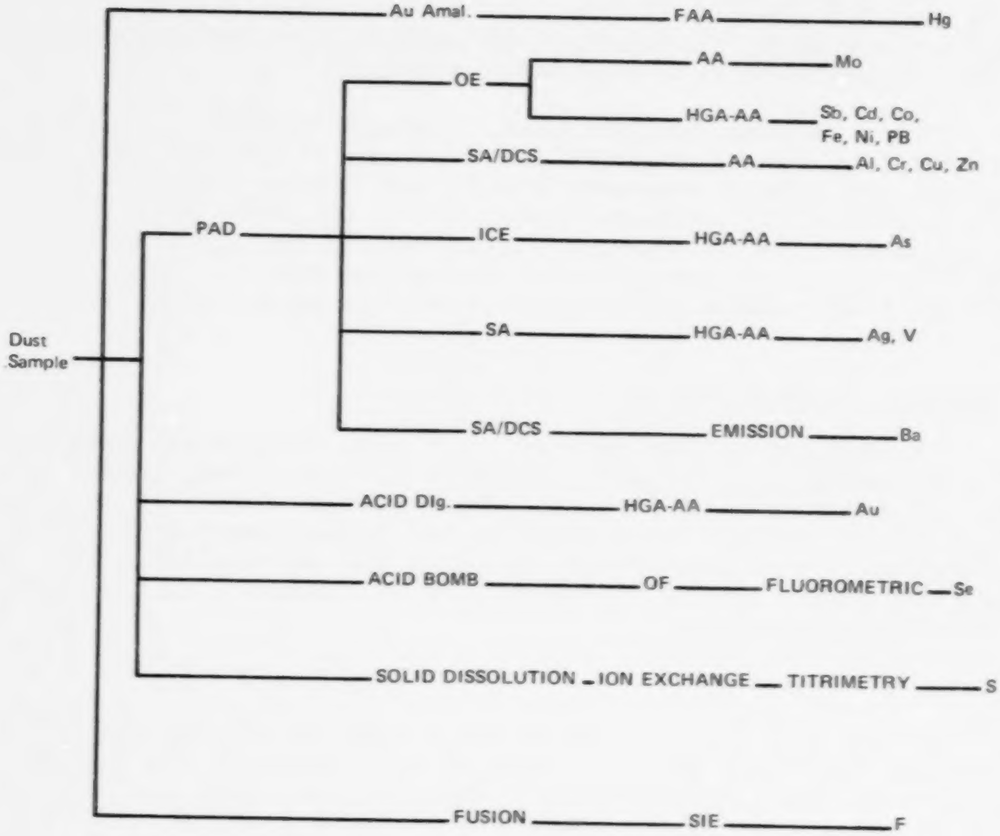
AA: ATOMIC ABSORPTION, FLAME
DI: DIRECT INJECTION
DCS: DOUBLE CAPILLARY SYSTEM
FAA: FLAMELESS ATOMIC ABSORPTION
HGA-AA: HEATED GRAPHITE ANALYZER OF THE ATOMIC ABSORPTION SPECTROPHOTOMETER
ICE: INORGANIC COMPLEX EXTRACTION
OE: ORGANIC EXTRACTION
PAD: PERCHLORIC ACID DIGESTION
SA: STANDARD ADDITIONS
SIE: SPECIFIC ION ELECTRODE

Figure B-4. Analytical Scheme for WEP Liquor.



AA: ATOMIC ABSORPTION, FLAME
DI: DIRECT INJECTION
DCS: DOUBLE CAPILLARY SYSTEM
FAA: FLAMELESS ATOMIC ABSORPTION
HGA-AA: HEATED GRAPHITE ANALYZER OF AA
ICE: INORGANIC COMPLEX EXTRACTION
OE: ORGANIC EXTRACTION
PAD: PERCHLORIC ACID DIGESTION
SA: STANDARD ADDITIONS
SIE: SPECIFIC ION ELECTRODE
ACID IMPINGER: 1:1:1: c.H_2SO_4, c.HNO_3, D.I WATER
BASIC IMPINGER: 20% KOH
H_2O_2 IMPINGER: 5% H_2O_2

Figure B-5. Analytical Scheme for Impinger Liquor.



AA:	ATOMIC ABSORPTION, FLAME
DI:	DIRECT INJECTION
DCS:	DOUBLE CAPILLARY SYSTEM
HGA-AA:	HEATED GRAPHITE ANALYZER OF THE ATOMIC ABSORPTION SPECTROPHOTOMETER
ICE:	INORGANIC COMPLEX EXTRACTION
OE:	ORGANIC EXTRACTION
PAD:	PERCHLORIC ACID DIGESTION
SA:	STANDARD ADDITIONS
SIE:	SPECIFIC ION ELECTRODE

Figure B-6. Analytical Scheme for Precipitator Dust.

Lithium borate fusion - A small amount of sample was fused with lithium borate. The cooled melt was dissolved in hydrochloric acid and hot water.

Most elements present in higher concentrations were analyzed from the lithium borate fusion. Elements present in trace concentrations were, in general, determined from solutions obtained from the perchloric acid digestion scheme.

There is some concern that volatile elements, such as arsenic, may have been partially lost by evaporation or sublimation during sample treatments with hot acids. However, it has been reported (C. Feldman, Anal. Chem. 49, 826, 1977) that no appreciable loss of arsenic occurs during the treatment of fly ash with acids at temperatures exceeding 200°C. Thus, it is assumed that losses of volatile elements were not of significant magnitude.

Elemental Determinations

The analytical procedures used were originally developed for the determination of trace elements in coal, coal ashes, sludges, and plant and animal tissues. The drastic change in the matrix observed in samples collected at the copper smelter necessitated screening of the procedures for accuracy and reliability. This task was accomplished by the method of standard addition and interference studies.

Silver and Vanadium--

Silver and vanadium were determined by the method of standard additions with the graphite furnace of the atomic absorption spectrophotometer. Samples used were the WEP liquor, the impinger solutions, and the perchloric acid solution of solids. There was no sample preconcentration needed for the determination.

Aluminum--

Aluminum was determined in the WEP liquor, the impinger solutions, and the perchloric acid solution of solids by AAS with the nitrous oxide-acetylene flame.

Arsenic--

The WEP liquor, the impinger solutions, and the perchloric acid solution of solids were used for the arsenic determination. Arsenic was complexed in an acidic medium as the heteropoly acid of molybdenum. The aqueous complex was injected into the heated graphite analyzer of the atomic absorption spectrophotometer. A charring temperature of 1200°C was used.

Gold--

Gold in solid samples was determined by direct injection into the heated graphite analyzer after the solids had been digested in a solution of hydrochloric and nitric acids. The WEP liquor and the impinger solutions were injected with no pretreatment.

Barium--

Samples from the WEP liquor, the impinger solutions, and the perchloric acid solution of solids were aspirated into the nitrous oxide-acetylene flame of the atomic absorption spectrophotometer in the emission mode. The method of standard additions with the double capillary system was used. Potassium salts were added to enhance the signal and mask interfering species.

Cadmium and Lead--

The double complexing agent of ammonium pyrrolidine dithiocarbamate and diethylammonium diethyldithiocarbamate was used to chelate lead and cadmium in aqueous solution. Lead and cadmium were extracted simultaneously with methyl isobutyl ketone (MIBK) from the WEP liquor, the impinger solutions, and the perchloric acid solution of solids. The extracted sample was injected into the graphite furnace attachment to the atomic absorption spectrophotometer.

Cobalt and Nickel--

Cobalt and nickel were chelated with diethyldithiocarbamate and then extracted with MIBK from the WEP liquor, the impinger solutions, or the perchloric acid solution of solids. The extracted sample was injected into the graphite furnace and determined by AAS.

Chromium, Copper, Iron and Zinc--

The four metals were determined by AAS with the air-acetylene flame. The samples were analyzed by the method of standard additions with a double capillary system. The WEP liquor, the impinger solutions, and the perchloric acid solution of solids were analyzed by this method.

Fluorine--

Solid samples were fused with sodium carbonate, and the melt was dissolved in deionized water. WEP liquor and impinger solutions were run directly. Final determination was done with a fluoride-specific ion electrode by the method of known additions to remove the effects of any interfering ions.

Mercury--

In the amalgamation method, gas samples were drawn through a plug of gold wool. Deamalgamation was accomplished by heating the gold wool. The released mercury was purged through the absorption cell of the atomic absorption spectrophotometer.

Solids were analyzed for mercury by weighing a sample into a platinum boat and heating the sample slowly in a chamber. The off-gases containing elemental mercury were purged through a gold plug. Deamalgamation and determination by AAS followed the same procedure as described above.

Liquid samples were acidified. Mercury was oxidized next with potassium permaganate. Hydroxylamine hydrochloride and stannous chloride were next used to reduce the mercury to the metallic state. Air was bubbled through the solution and passed through the absorption cell of the atomic absorption spectrophotometer.

Molybdenum--

Molybdenum was complexed as the thiocyanate, extracted into MIBK, and aspirated into the nitrous oxide-acetylene flame of the atomic absorption spectrophotometer. Ascorbic acid and sodium fluoride were used to mask interference from iron and titanium.

Antimony--

Antimony was extracted as the iodide into a mixture of tributylphosphate and MIBK. Extraction was performed on the WEP liquor, the impinger solutions, and the perchloric acid solution of solids. Sulfamic acid was added to the acid impinger solution prior to extraction to remove the nitrates. Peroxide impinger solutions were boiled prior to extraction to decompose the hydrogen peroxide. The extracted solution was injected into a graphite tube of the atomic absorption spectrophotometer, which had been coated with ammonium molybdate.

Selenium--

Solid samples were digested in a Teflon bomb with nitric acid and perchloric acid. Following the digestion, the sample was heated with dilute hydrochloric acid. WEP liquors and impinger solutions were also heated with HCl. Extraction procedures for all samples were the same from this point forward. Following stabilization with formic acid, hydroxylamine, and EDTA, the samples were complexed with 2,3-diaminonaphthalene. The selenium complex was extracted into cyclohexane and measured on a fluorometer.

ANALYTICAL RESULTS

The analytical data for the liquors from the WEP train (the combination of dissolved solids and original liquor, on one hand, and the combination of impinger solutions) are given in Table B-3. Also given in this table are data for the impingers used in the vapor sampling train. Calculated concentrations of the elements in the units $lb/10^6$ scf are given in Table B-4; values recalculated in the units mg/m^3 are given in the body of this report.

TABLE B-3. ELEMENTAL CONCENTRATIONS (μg/g)[a] IN SEPARATE FRACTIONS COLLECTED IN THE WEP AND VAPOR SAMPLING TRAINS

	ESP INLET						ESP OUTLET			STACK	
	WEP liquor	WEP impingers	WEP liquor	WEP impingers	WEP liquor	WEP impingers	WEP liquor	WEP impingers	Vapor train impingers	WEP liquor	WEP impingers
Date	Jan. 12	Jan. 12	Jan. 14	Jan. 14	Jan. 15	Jan. 15	Jan. 12	Jan. 12	Jan. 11, 12, 14	Jan. 14, 15	Jan. 14, 15
Radian No	947	948	953	954	951	959	949	950	957	955	956
Weight (grams)	1384.03	1287.57	1416.49	1208.59	1275.00	1209.34	628.19	1389.62	1659.90	1192.10	1411.11
Ag	0.94	<0.01	0.22	0.13	0.81	0.15	0.039	0.23	0.080	0.62	0.25
Al	66.0	0.82	110.0	0.66	32.0	<0.1	4.1	0.5	1.6	3.8	0.1
As	26.0	0.098	56.0	0.29	26.0	0.22	48.0	0.059	54.0	56.0	0.050
Au	0.002	<0.0005	0.0005	0.002	0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.0008	0.0005
Ba	<0.6	<0.8	<0.6	<0.9	<0.1	<0.1	<0.1	<0.3	<0.1	<0.3	<0.1
Cd	9.0	0.006	25.0	0.086	5.0	0.019	1.2	0.002	0.002	1.6	0.001
Co	0.13	<0.001	0.92	<0.001	0.13	0.015	0.029	<0.001	<0.001	0.018	<0.001
Cr	0.59	0.10	1.90	0.12	1.1	0.11	0.12	0.128	0.10	0.19	0.071
Cu	530.0	0.20	1114.0	1.7	560.0	1.4	21.0	0.11	0.47	49.0	0.23
F	190.0	3.2	170.0	1.1	120.0	1.5	420.0	2.5	240.0	320.0	3.3
Fe	590.0	0.28	1400.0	0.20	550.0	0.22	14.0	0.10	0.66	23.0	0.24
Hg	<0.01	<0.01	0.027	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mo	60.0	0.041	82.0	0.28	28.0	0.098	4.6	0.012	0.033	7.6	0.046
Ni	0.47	<0.01	3.1	<0.01	0.60	<0.01	0.48	0.011	0.015	<0.01	<0.01
Pb	51.0	0.06	72.0	0.10	30.0	0.070	0.77	<0.05	0.024	6.0	<0.05
Sb	5.8	0.003	6.9	0.012	3.6	0.015	0.88	0.012	0.014	1.1	0.010
Se	1320 ppb	9.7 ppb	3960 ppb	15 ppb	940 ppb	8.6 ppb	43 ppb	11 ppb	1.4 ppb	17 ppb	0.51 ppb
V	0.25	0.43	0.36	0.54	0.15	0.87	0.42	0.81	0.49	0.010	2.5
Zn	54.0	0.14	11.0	0.54	45.0	0.18	8.6	0.030	0.026	13.0	0.23

a. Fraction of the sample weight shown in the third row of data. This value is of primary interest in showing the distribution of elements in different sampling devices. It is related to the stack gas concentration through an unspecified volume of gas sampled.

TABLE B-4. TOTAL ELEMENTAL CONCENTRATIONS (lb/10^6 scf)[a] CALCULATED FROM ANALYSES OF SAMPLES COLLECTED IN THE WEP AND VAPOR SAMPLING TRAINS

	ESP INLET			ESP OUTLET		STACK
Date	Jan. 12	Jan. 14	Jan. 15	Jan. 12	Jan. 11, 12, 14	Jan. 14, 15
Sampling Method	WEP	WEP	WEP	WEP	Vapor train	WEP
Sample Volume (scf)	100.08	96.54	92.76	126.64	309.34	275.83
Ag	0.029	0.011	0.029	0.006	0.00095	0.0087
Al	1.9	3.4	1.0	0.058	0.019	0.036
As	0.79	1.8	0.78	0.530	0.64	0.54
Au	6.1×10^{-5}	0.00027	6.2×10^{-5}	2×10^{-6}	6×10^{-6}	1.3×10^{-5}
Ba	<0.4	<0.04	<0.006	<0.003	<0.001	<0.003
Cd	0.270	0.82	0.150	0.013	2.4×10^{-5}	0.015
Co	0.0041	0.030	0.0045	0.00013	$<1 \times 10^{-5}$	0.00020
Cr	0.021	0.066	0.035	0.0044	0.0012	0.0026
Cu	16.0	37.0	17.0	0.230	0.0056	0.47
F	5.5	5.2	3.6	4.4	2.9	3.0
Fe	18	45	17	0.15	0.0078	0.22
Hg	-	7.1×10^{-5}[b]	0.001[b]	-	0.00028[b]	0.00011[b]
Mo	1.8	2.7	0.850	0.051	0.00039	0.073
Ni	0.014	0.099	0.018	0.0055	0.00018	<0.0002
Pb	1.6	2.3	0.910	0.0084	0.00028	0.058
Sb	0.18	0.22	0.110	0.0099	0.00017	0.011
Se	0.041	0.13	0.048	0.00073	1.7×10^{-5}	0.011
V	0.020	0.027	0.030	0.024	0.0058	0.00017
Zn	1.7	0.360	1.4	0.095	0.00031	0.12

a. At 60°F and 29.92 in. Hg. Recalculated for body of report in mg/m^3 for 21°C (70°F) and 760 mmHg.

b. Based on samples collected by the amalgamation technique.

APPENDIX C

CHEMICAL SAMPLING AND ANALYSIS BY SOUTHERN RESEARCH INSTITUTE

SAMPLING TRAINS

Trace Elements: Gaseous and Particulate

ESP inlet--

The sampling train for trace elements in the gaseous and particulate states consisted of components located inside and outside the flue-gas duct, as shown schematically in Figure C-1. The internal portion of the train consisted of a series of three cyclones with nominal cut points of 10, 3 and 1 μm; a glass-fiber thimble; and a 6-ft stainless steel probe. Outside of the stack, the probe was connected to a flexible Teflon transfer line maintained at 200°C (400°F), which, in turn, was attached to a glass-fiber filter in a 120°C (250°F) oven. A 4-in. length of stainless steel tubing was placed between the end of the Teflon line and the entrance to the oven. This tubing acted as a heat exchanger in lowering gas temperatures to 120°C at the face of the filter. A small thermocouple in the filter holder was used to monitor gas temperatures. Trace-element vapors passing through the filter were drawn into a series of seven Greenburg-Smith impingers in an ice bath. The first two impingers contained about 75 and 160 ml, respectively, of a 1:1:1 mixture of sulfuric acid, nitric acid, and water. The third and seventh impingers were dry. The fourth impinger contained 250 ml of a 30% solution of hydrogen peroxide, and the fifth and sixth impingers were filled with 200 ml of a 7% solution of potassium hydroxide. The remainder of the train consisted of a condensate collector, a calibrated orifice with a water manometer, a mercury manometer, a dry gas meter, and a vacuum pump.

ESP outlet--

The sampling train used at the precipitator outlet was essentially the same as described above except a single cyclone (1 μm) was substituted for the three-cyclone set and a 47-mm glass-fiber filter disc was used in place of the glass-fiber thimble.

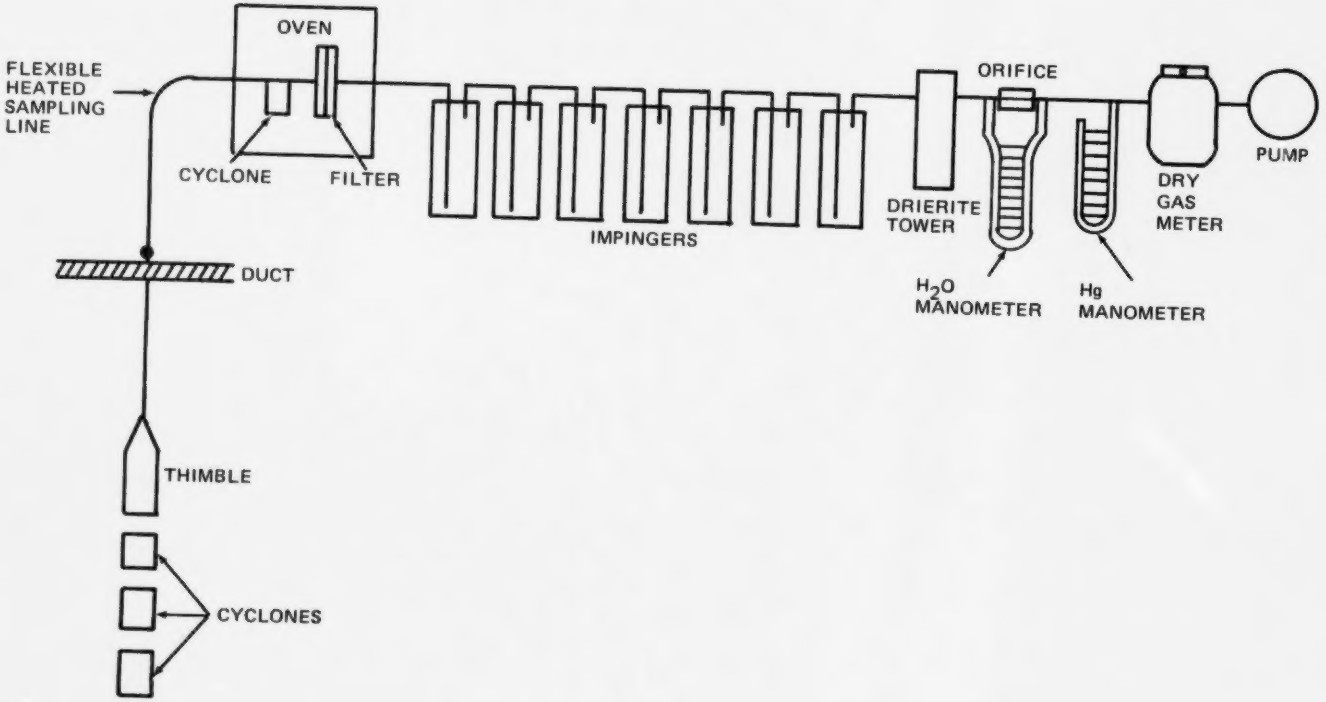


Figure C-1. Schematic diagram of cyclone-filter impinger sampling train.

Mercury Vapor

Mercury vapor was sampled by drawing flue gas through, in sequence, a glass-lined heated probe with a quartz-wool filter plug, a saturated sodium carbonate bubbler (to remove sulfur oxides), and two bubblers containing a solution of 3% potassium permanganate in 5% nitric acid. The carbonate scrubber proved to be effective in removing the sulfur oxides and showed no tendency to absorb mercury. At a sampling rate of about 1 ℓ/min the collection efficiency of the first permanganate bubbler averaged only 76% in the field test, as opposed to 99% in laboratory experiments. This comparison suggests that the mercury concentration in the flue gas, as determined by this method, quite possibly is low. Unless otherwise stated, the results given for mercury are based on samples obtained with the cyclone-filter-impinger train rather than the permanganate bubbler.

Sulfur Oxides

Sulfur oxides were collected by the controlled condensation method for sulfur trioxide and an absorption method for sulfur dioxide. This procedure consisted of drawing flue gas through a heated glass-lined sampling probe, with a quartz-wool filter plug to remove particulate, into a condenser. The condenser was maintained at 60 to 90°C, a temperature below the dew point of sulfur trioxide as sulfuric acid but above the dew point of water vapor. Thus, sulfuric acid was retained in the condenser while sulfur dioxide was swept into a 3% hydrogen peroxide bubbler to be converted to sulfuric acid. The remainder of the train consisted of a drying tower, a dry test meter, and a vacuum pump. The total sulfate content of the condenser and bubbler samples was determined by a barium perchlorate titration with Thorin indicator.

Other Gases

Carbon dioxide and oxygen were determined with an Orsat apparatus. Water vapor was determined by collection in a tared Drierite absorption tube.

Sampling Schedule

Sampling runs with the trace-element train were conducted at the outlet of the electrostatic precipitator on January 12 and 14, 1977, and at the inlet to the precipitator on January 15 and 16, 1977. Simultaneous samples were collected by Radian Corporation using the wet electrostatic precipitator sampling system. Because of space limitations, the probes for the two trains could not be inserted into the same sampling port; instead, they were inserted into adjacent sampling ports in both test locations. Sulfur oxide, mercury, and Orsat samples were obtained from an additional port. The schedule for sample collection is shown in Table C-1.

METHODS FOR TRACE ELEMENTS

Sample Preparation

Samples returned to the laboratory for analysis included cyclone, thimble, and filter solids, and impinger solutions from both the trace-element and mercury sampling trains. The acid, base, and peroxide impingers from the trace-element train were combined on all except the January 14 run. For this set of samples, the acid, the base, the peroxide impingers were kept separate in order to determine the distribution of the trace metals in the various types of collection media.

Acid attack--

Several acids and combinations of acids were screened for effectiveness in dissolving the hopper sample. The more promising procedures were then modified into a method subsequently referred to as the standard acid attack. This method, described below, was used to process all the cyclone and hopper samples collected during the test program.

A 0.500 g sample, or a lesser weight depending on the availability of material, was added to a Teflon beaker containing 10 ml of concentrated sulfuric acid and 5 ml of concentrated nitric acid. The mixture was slowly taken to fumes of sulfur trioxide and cooled, and an additional 10 ml of concentrated nitric acid was added. The sample was again taken to fumes of sulfur trioxide and cooled, and 2 ml of 72% perchloric acid was added. After being taken to fumes of perchloric acid, the residue was digested with distilled water and filtered through a 0.45 μm membrane filter.

The filter was transferred to a platinum crucible and attacked with 3 ml of 40% hydrofluoric acid. Then, 3 ml of concentrated nitric acid was added, and the sample was digested. Next, an addition of 2 ml of 72% perchloric acid was made and the sample was further digested. Finally, the sample was diluted with water, again digested, and combined with the original filtrate and diluted to a volume of 250 ml.

With those samples in abundant supply, a second type of acid attack was used for a comparatively study. This method consisted of digesting a 0.500 g sample of 10 ml of aqua regia and 1 ml of 72% perchloric acid in a Teflon beaker. After being taken to fumes of perchloric acid, the sample was cooled, diluted with water, and filtered. The filter was discarded, and the filtrate diluted to 250 ml.

TABLE C-1. SCHEDULE FOR SAMPLING BY SOUTHERN RESEARCH INSTITUTE

Date	Location	Train	Time, hr	Gas temp, °C	Volume sampled, m^3
Jan 12	Outlet	Trace element	1100-1730	179	5.0
		Sulfur oxides	1000-1100	171	0.037
			1130-1230	174	0.069
			1700-1720	188	0.043
		Mercury	1320-1630	182	0.164
Jan 14	Outlet	Trace element	930-1430	177	4.2
		Sulfur oxides	1000-1100	177	0.079
			1135-1315	177	0.124
			1615-1700	179	0.055
		Mercury	1350-1535	177	0.091
Jan 15	Inlet	Trace element	945-1345	241	2.4
		Sulfur oxides	1345-1500	266	0.063
		Mercury	1530-1700	271	0.079
Jan 16	Inlet	Trace element	955-1440	246	1.9
		Sulfur oxides	1200-1300	243	0.018
		Mercury	1330-1630	243	0.084

Neither the in-stack thimble and filter nor the out-of-stack filter collected sufficient particulate to enable a sample to be separated from the glass-fiber matrix. Therefore, the entire filter or thimble was extracted by an overnight reflux with 20-30 ml of aqua regia. Each sample was then filtered through a 0.45 μm membrane filter and diluted to 100 ml with deionized water.

A question of possible loss of volatile elements during hot acid treatment was addressed in the discussion of Radian's sample dissolution methods. The loss is assumed to be negligible for reasons already cited in Appendix B.

Fusion attack--

An attempt was made to dissolve the hopper samples in several types of fluxes including potassium pyrosulfate, sodium tetraborate, lithium metaborate, sodium carbonate, and sodium hydroxide. Based on the quantity of insoluble material remaining after the fusion, none of these procedures were considered satisfactory for preparing samples for a complete analysis. The sodium hydroxide attack, however, was used to solubilize particulates for fluorine determination.

Elemental Determinations

Most of the analyses were conducted by use of a Perkin-Elmer Model 603 atomic absorption spectrophotometer, which could be used when appropriate with an HGA-2100 graphite furnace. The method of addition was used in each procedure as a means of reducing potential interferences.

Silver, aluminum, cadmium, chromium, copper, iron, nickel, and zinc--

Aluminum was determined by atomic absorption spectrometry (AAS) with a nitrous oxide-acetylene flame. A 0.2% KCl solution was added to the samples to control ionization. The remaining metals were also determined by AAS but with an air-acetylene flame and a 4-inch single-shot burner head. Scale expansion was used to increase the sensitivity of the instrument when necessary.

Arsenic--

Arsenic in the impinger, filter and thimble samples was determined by AAS with air-acetylene flame, a D_2 background corrector, and an electrodeless discharge lamp.

Gold--

The gold content of the impinger, cyclone, and hopper samples was determined by the method of Strong and Murray-Smith (Talanta 21, 1253 (1974)). This procedure was based on an extraction of the gold with MIBK from a sample made 20% in HCl. The sensitivity of the method was increased by the use of the graphite furnace instead of flame atomic absorption. The filter and thimble samples were not analyzed for gold since an excessive amount of the limited volume of sample would have been expended.

Barium--

The graphite furnace was used to determine the barium concentration in the impinger, hopper, and cyclone samples. The thimble and filter samples were not run because the entire volume of these solutions had been used for other analyses.

Cobalt--

The impinger, hopper, and cyclone samples were analyzed with the graphite furnace. The filter and thimble samples were analyzed by AAS with an air-acetylene flame.

Fluorine--

All determinations of this element as fluoride were made by means of an Orion Model 94-09A fluoride-specific ion electrode, a conventional saturated potassium chloride reference electrode, and a Corning Model 12 expanded-scale pH meter. The impinger solutions were adjusted to pH 6; then 1 M sodium citrate was added to act both as a buffer and a complexing agent for aluminum and iron. The hopper and cyclone samples were fused with sodium hydroxide in a nickel crucible, digested overnight with water, and then dissolved in 1 M hydrochloric acid prior to analysis. No attempt was made to analyze the filter or thimble samples, and only the cyclone catches at the precipitator inlet contained enough material for this type of analysis.

Mercury--

The impinger samples from the mercury and trace-element sampling trains were analyzed for mercury by the cold vapor technique of Hatch and Ott (Anal. Chem. 40, 2085 (1968)) Because of interference problems, this method was unsatisfactory for the cyclone, hopper, thimble and filter samples; therefore, a procedure of Tindall (Atomic Absorption Newsletter 16 (2), 38 (1977)) was adopted. This method was based on the conversion of mercury to a tetraiodomercurate ion in an ammoniacal state followed by the extraction of the complex into MIBK. The extract was then analyzed by AAS with an air-acetylene flame.

Molybdenum--

The molybdenum content of the impinger solutions was determined with the graphite furnace, while the remaining samples were analyzed by AAS with a nitrous oxide-acetylene flame.

Lead and Antimony--

Lead and antimony contents of the impinger solutions were determined by the procedure of Burke (Analyst 97, 19 (1972)). Both of these elements were quantitatively extracted from a 10% hydrochloric acid solution of the sample containing 2% ascorbic acid and 6% of potassium iodide in a single extraction with a 5% solution of trioctylphosphine oxide in MIBK. The extract was nebulized directly into the burner of the atomic absorption spectrophotometer. The remaining samples were analyzed without resorting to the extraction procedure.

Selenium--

The graphite furnace was used to analyze the hopper, cyclone, filter, and thimble samples for selenium. Nickel was added to the samples to prevent the loss of selenium during the charring cycle. Since the high sulfate content in the impinger solutions caused severe interference problems with this method, these samples were analyzed by the diaminonaphthalene procedure of Lott, *et al* (*Anal. Chem.* 35, (1963)).

Vanadium--

The vanadium content of all samples was determined by AAS with the graphite furnace.

ANALYTICAL RESULTS FOR TRACE ELEMENTS

The results of individual samples collected at the ESP inlet and outlet in the cyclone-filter-impinger sampling trains are given in Tables C-2, C-3, C-4, and C-5.

TABLE C-2. ELEMENTAL CONCENTRATIONS CALCULATED FOR SAMPLES COLLECTED AT THE OUTLET DUCT ON JANUARY 12, 1977

	Concentration,[a] mg/m^3			
Element	Cyclone in duct	Filter in duct	Filter outside duct	Impinger outside duct
Ag	0.006	<0.002	<0.003	<0.01
Al	0.32	0.19	0.22	0.15
As	0.265	0.082	0.10	6.3
Au	<0.001	-[b]	-[b]	<0.001
Ba	<0.003	-[b]	-[b]	<0.02
Cd	0.12	0.020	<0.001	<0.01
Co	<0.005	<0.001	<0.001	<0.015
Cr	0.022	0.003	<0.001	<0.01
Cu	7.0	1.1	0.007	0.046
F	-[b]	-[b]	-[b]	21
Fe	3.0	0.10	0.014	0.09
Hg	<0.001	<0.001	<0.001	0.008
Mo	0.48	0.13	<0.002	<0.03
Ni	0.037	<0.001	<0.001	<0.01
Pb	0.20	0.15	0.002	<0.01
Sb	0.12	0.030	<0.01	<0.01
Se	0.027	0.009	<0.004	0.027
V	<0.002	<0.001	<0.001	<0.03
Zn	1.6	0.54	0.24	0.006

a. At 21°C (70°F) and 760 mmHg.
b. Not determined.

TABLE C-3. ELEMENTAL CONCENTRATIONS CALCULATED FOR SAMPLES COLLECTED AT THE OUTLET DUCT ON JANUARY 14, 1977

Element	Concentration,[a] mg/m^3				
	Cyclone in duct	Filter[b] outside duct	Impingers outside duct		
			acid	Peroxide	base
Ag	0.004	<0.002	<0.01	<0.01	<0.01
Al	0.20	0.20	0.12	<0.015	<0.015
As	0.039	0.18	7.0	0.056	<0.01
Au	<0.001	–[c]	<0.001	<0.001	<0.001
Ba	<0.003	–[c]	<0.025	<0.025	<0.025
Cd	0.088	0.011	<0.005	<0.005	<0.005
Co	<0.005	<0.001	<0.005	<0.005	<0.005
Cr	0.017	0.005	<0.01	<0.01	<0.01
Cu	4.6	1.0	0.028	0.023	<0.016
F	–[c]	–[c]	23	0.009	12
Fe	2.3	0.064	0.039	0.006	<0.006
Hg	<0.001	<0.001	0.009	<0.001	<0.001
Mo	0.31	0.10	<0.01	<0.01	<0.01
Ni	0.024	<0.001	<0.01	<0.01	<0.01
Pb	0.23	0.075	<0.005	<0.005	<0.005
Sb	0.048	<0.01	<0.015	<0.015	<0.015
Se	0.014	<0.005	0.031	<0.005	<0.01
V	<0.002	<0.001	<0.01	<0.01	<0.01
Zn	0.80	0.45	0.008	0.008	0.005

a. At 21°C (70°F) and 760 mmHg.

b. Sample on filter inside duct was lost; because of this, the data in this table are not included in the body of this report.

c. Not determined.

TABLE C-4. ELEMENTAL CONCENTRATIONS CALCULATED FOR SAMPLES COLLECTED AT THE INLET DUCT ON JANUARY 15, 1977

	Concentration,[a] mg/m^3			
Element	Cyclone in duct	Filter in duct	Filter outside duct	Impinger outside duct
Ag	0.079	0.046	<0.003	<0.02
Al	25.9	-[b]	<0.03	0.22
As	2.0	2.1	0.082	8.5
Au	0.001	-[b]	-[b]	<0.001
Ba	0.070	-[b]	-[b]	<0.04
Cd	0.62	0.58	<0.001	<0.01
Co	0.044	<0.001	<0.001	<0.03
Cr	0.40	0.12	<0.001	<0.02
Cu	271	50	0.011	0.076
F	0.57	-[b]	-[b]	33
Fe	242	3.5	0.015	0.11
Hg	<0.001	<0.001	<0.001	0.011
Mo	8.5	4.4	<0.005	<0.06
Ni	0.47	0.024	0.005	<0.02
Pb	3.3	1.1	<0.005	<0.03
Sb	0.73	0.33	<0.02	<0.025
Se	0.82	0.16	<0.01	0.081
V	0.062	0.007	<0.001	<0.06
Zn	12	11	0.054	0.031

a. At 21°C (70°F) and 760 mmHg.
b. Not determined.

TABLE C-5. ELEMENTAL CONCENTRATIONS CALCULATED FOR SAMPLES COLLECTED AT THE INLET DUCT ON JANUARY 16, 1977

Element	Concentration,[a] mg/m^3			
	Cyclone in duct	Filter in duct	Filter outside duct	Impinger outside duct
Ag	0.28	0.036	<0.003	<0.02
Al	80	–[b]	1.5	0.34
As	9.1	4.7	1.4	8.2
Au	<0.001	–[b]	–[b]	<0.001
Ba	0.38	–[b]	–[b]	<0.04
Cd	6.2	3.2	<0.001	<0.01
Co	0.083	<0.001	<0.001	<0.03
Cr	0.78	0.10	<0.002	<0.02
Cu	930	26	0.015	0.12
F	1.9	–[b]	–[b]	59
Fe	833	2.9	0.046	0.16
Hg	<0.001	<0.001	<0.001	0.021
Mo	27	3.9	<0.005	<0.06
Ni	1.42	0.022	0.064	<0.02
Pb	19	6.3	<0.005	<0.03
Sb	3.2	0.32	<0.03	<0.025
Se	2.8	0.034	<0.01	0.20
V	0.17	0.004	<0.001	<0.06
Zn	42	10	1.6	0.015

[a] At 21°C (70°F) and 760 mmHg.

[b] Not determined.

APPENDIX D

INLET AND OUTLET CASCADE IMPACTOR COMPUTER DATA SHEETS

The data for the size distribution samples taken by cascade impactors is given in this Appendix. Sampling time ranged from 30 to 40 minutes at the inlet side of the control device and from 75 to 135 minutes at the outlet.

Inlet Samples				Outlet Samples			
Date	Time	Part	Page	Date	Time	Part	Page
1-12-77	1257	2	141	1-12-77	1015	5	153
1-12-77	1423	2	142	1-12-77	1015	4	154
1-12-77	1500	2	143	1-12-77	1435	5	155
1-14-77	1005	2	144	1-14-77	1016	4	156
1-14-77	1252	2	145	1-14-77	1145	5	157
1-14-77	1409	2	146	1-14-77	1145	4	158
1-15-77	1315	2	147	1-15-77	1000	4	159
1-15-77	1357	2	148	1-15-77	1000	5	160
1-15-77	1448	2	149	1-15-77	1410	4	161
1-16-77	1255	2	150	1-16-77	0915	4	162
1-16-77	1341	2	151	1-16-77	1345	4	163
1-16-77	1440	2	152	1-16-77	1345	5	164

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KCCI-1  1-12-77  PORT-2  1257                                       INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - C

IMPACTOR FLOWRATE = 0.092 ACFM            IMPACTOR TEMPERATURE =  470.0 F = 243.3 C             SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 2.7 IN. OF HG       STACK TEMPERATURE =  470.0 F = 243.3 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)           CO2 =  6.47          CO =  0.00           N2 = 77.98          O2 =  8.05            H2O =  7.50

CALC. MASS LOADING = 2.0202E-01 GR/ACF            4.0639E-01 GR/DNCF             4.6229E+02 MG/ACM             9.2996E+02 MG/DNCM

IMPACTOR STAGE                               CYC       S0        S1        S2        S3        S4        S5                FILTER

STAGE INDEX NUMBER                            1         2         3         4         5         6         7                  8

D50 (MICROMETERS)                           7.79      4.67      2.51      1.55      1.17      0.46      0.31

MASS (MILLIGRAMS)                          11.80      3.31      5.53      2.31      1.51      3.19      4.05                4.43

MG/DNCM/STAGE                             3.08E+02  8.64E+01  1.44E+02  6.03E+01  3.94E+01  8.32E+01  1.06E+02            1.16E+02

CUM. PERCENT OF MASS SMALLER THAN D50    67.34     58.18     42.87     36.48     32.30     23.47     12.26

CUM. (MG/ACM) SMALLER THAN D50            3.11E+02  2.69E+02  1.98E+02  1.69E+02  1.49E+02  1.09E+02  5.67E+01

CUM. (MG/DNCM) SMALLER THAN D50           6.26E+02  5.41E+02  3.99E+02  3.39E+02  3.00E+02  2.18E+02  1.14E+02

CUM. (GR/ACF) SMALLER THAN D50            1.36E-01  1.18E-01  8.66E-02  7.37E-02  6.53E-02  4.74E-02  2.48E-02

CUM. (GR/DNCF) SMALLER THAN D50           2.74E-01  2.36E-01  1.74E-01  1.48E-01  1.31E-01  9.54E-02  4.98E-02

GEO. MEAN DIA. (MICROMETERS)              2.41E+01  6.03E+00  3.42E+00  1.97E+00  1.35E+00  7.32E-01  3.79E-01            8.41E-02

DM/DLOGD (MG/DNCM)                        3.14E+02  3.89E+02  5.35E+02  2.90E+02  3.22E+02  2.04E+02  6.49E+02            3.84E+02

DN/DLOGD (NO. PARTICLES/DNCM)             2.34E+07  1.84E+09  1.39E+10  3.90E+10  1.36E+11  5.39E+11  1.23E+13            6.71E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

  SQUARE ROOTS OF PSI BY STAGE                         0.322     0.322     0.351     0.388     0.330     0.350     0.273

  HOLE DIAMETERS BY STAGE (CENTIMETERS)                0.3658    0.2460    0.1724    0.1360    0.0896    0.0719    0.0589
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KCCI-3  1-12-77  PORT-2  1423                                         INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER = A

IMPACTOR FLOWRATE = 0.078 ACFM              IMPACTOR TEMPERATURE =  470.0 F = 243.3 C              SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 2.0 IN. OF HG      STACK TEMPERATURE =  470.0 F = 243.3 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)            CO2 =  6.47          CO =  0.00          N2 = 77.98          O2 =  8.05          H2O =  7.50

CALC. MASS LOADING = 2.5793E-01 GR/ACF            5.1887E-01 GR/DNCF            5.9024E+02 MG/ACM            1.1873E+03 MG/DNCM

IMPACTOR STAGE                             CYC       S0        S1        S2        S3        S4        S5                  FILTER

STAGE INDEX NUMBER                          1         2         3         4         5         6         7                    8

D50 (MICROMETERS)                          8.46      4.86      2.67      1.72      1.13      0.36      0.30

MASS (MILLIGRAMS)                         15.76      5.63      5.29      2.15      2.77      0.13      3.79                 3.59

MG/DNCM/STAGE                            4.85E+02  1.73E+02  1.63E+02  6.62E+01  8.52E+01  4.00E+00  1.17E+02             1.10E+02

CUM. PERCENT OF MASS SMALLER THAN D50    59.70     45.31     31.78     26.28     19.20     18.87      9.18

CUM. (MG/ACM) SMALLER THAN D50           3.52E+02  2.67E+02  1.88E+02  1.55E+02  1.13E+02  1.11E+02  5.42E+01

CUM. (MG/DNCM) SMALLER THAN D50          7.09E+02  5.38E+02  3.77E+02  3.12E+02  2.28E+02  2.24E+02  1.09E+02

CUM. (GR/ACF) SMALLER THAN D50           1.54E-01  1.17E-01  8.20E-02  6.78E-02  4.95E-02  4.87E-02  2.37E-02

CUM. (GR/DNCF) SMALLER THAN D50          3.10E-01  2.35E-01  1.65E-01  1.36E-01  9.96E-02  9.79E-02  4.76E-02

GEO. MEAN DIA. (MICROMETERS)             2.51E+01  6.41E+00  3.60E+00  2.14E+00  1.39E+00  6.38E-01  3.26E-01             6.46E-02

DM/DLOGD (MG/DNCM)                       5.14E+02  7.21E+02  6.26E+02  3.45E+02  4.72E+02  8.02E+00  1.39E+03             3.67E+02

DN/DLOGD (NO. PARTICLES/DNCM)            3.38E+07  2.84E+09  1.39E+10  3.64E+10  1.81E+11  3.21E+10  4.17E+13             1.41E+15


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

  SQUARE ROOTS OF PSI BY STAGE                     0.322     0.322     0.338     0.345     0.258     0.317     0.229

  HOLE DIAMETERS BY STAGE (CENTIMETERS)            0.3554    0.2422    0.1779    0.1364    0.0884    0.0705    0.0556
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KCCI-4  1-12-77  PORT-2  1500
                                                                 INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER = D
IMPACTOR FLOWRATE = 0.085 ACFM          IMPACTOR TEMPERATURE =  470.0 F = 243.3 C               SAMPLING DURATION =  30.00 MIN
IMPACTOR PRESSURE DROP = 2.3 IN. OF HG       STACK TEMPERATURE =  470.0 F = 243.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  6.47          CO =  0.00          N2 = 77.98          O2 =  8.05          H2O =  7.50
CALC. MASS LOADING = 1.5953E-01 GR/ACF            3.2092E-01 GR/DNCF            3.6506E+02 MG/ACM            7.3436E+02 MG/DNCM
IMPACTOR STAGE                             CYC        S0         S1         S2         S3         S4         S5              FILTER
STAGE INDEX NUMBER                          1          2          3          4          5          6          7                 8
D50 (MICROMETERS)                         8.10       4.66       2.62       1.68       1.12       0.46       0.33
MASS (MILLIGRAMS)                        10.76       3.07       2.93       1.61       1.03       3.93       3.03              0.00
MG/DNCM/STAGE                          3.04E+02   8.67E+01   8.27E+01   4.55E+01   2.91E+01   1.11E+02   8.56E+01          0.00E-01
CUM. PERCENT OF MASS SMALLER THAN D50  59.18      47.53      36.42      30.31      26.40      11.49       0.00
CUM. (MG/ACM) SMALLER THAN D50         2.16E+02   1.74E+02   1.33E+02   1.11E+02   9.64E+01   4.20E+01   0.00E-01
CUM. (MG/DNCM) SMALLER THAN D50        4.35E+02   3.49E+02   2.67E+02   2.23E+02   1.94E+02   8.44E+01   0.00E-01
CUM. (GR/ACF) SMALLER THAN D50         9.44E-02   7.58E-02   5.81E-02   4.84E-02   4.21E-02   1.83E-02   0.00E-01
CUM. (GR/DNCF) SMALLER THAN D50        1.90E-01   1.53E-01   1.17E-01   9.73E-02   8.47E-02   3.69E-02   0.00E-01
GEO. MEAN DIA. (MICROMETERS)           2.45E+01   6.15E+00   3.49E+00   2.10E+00   1.37E+00   7.16E-01   3.92E-01          5.55E-02
DM/DLOGD (MG/DNCM)                     3.15E+02   3.61E+02   3.30E+02   2.36E+02   1.64E+02   2.87E+02   6.24E+02          0.00E-01
DN/DLOGD (NO. PARTICLES/DNCM)          2.21E+07   1.62E+09   8.04E+09   2.65E+10   6.63E+10   8.13E+11   1.08E+13          0.00E-01

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                   0.322      0.322      0.346      0.354      0.297      0.337      0.226
  HOLE DIAMETERS BY STAGE (CENTIMETERS)          0.3560     0.2461     0.1778     0.1368     0.0937     0.0739     0.0550
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KCCI-5  1-14-77  PORT-2  1005                                         INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - D
IMPACTOR FLOWRATE = 0.108 ACFM            IMPACTOR TEMPERATURE =  470.0 F = 243.3 C                 SAMPLING DURATION =  30.00 MIN
IMPACTOR PRESSURE DROP = 3.8 IN. OF HG      STACK TEMPERATURE =  470.0 F = 243.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG      MAX. PARTICLE DIAMETER =   74.4 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  6.55          CO =  0.00           N2 = 77.36           O2 =  8.30            H2O =  7.80
CALC. MASS LOADING = 1.6866E-01 GR/ACF              3.4039E-01 GR/DNCF             3.8595E+02 MG/ACM                7.7893E+02 MG/DNCM
IMPACTOR STAGE                            CYC         S0         S1         S2         S3         S4         S5                  FILTER
STAGE INDEX NUMBER                         1          2          3          4          5          6          7                    8
D50 (MICROMETERS)                        7.18       4.12       2.31       1.47       0.97       0.39       0.28
MASS (MILLIGRAMS)                       10.76       3.56       3.42       2.12       2.18       7.12       3.78                 2.47
MG/DNCM/STAGE                         2.40E+02   7.94E+01   7.63E+01   4.73E+01   4.86E+01   1.59E+02   8.43E+01             5.51E+01
CUM. PERCENT OF MASS SMALLER THAN D50  69.61      59.56      49.90      43.91      37.76      17.65       6.98
CUM. (MG/ACM) SMALLER THAN D50        2.69E+02   2.30E+02   1.93E+02   1.69E+02   1.46E+02   6.81E+01   2.69E+01
CUM. (MG/DNCM) SMALLER THAN D50       5.42E+02   4.64E+02   3.89E+02   3.42E+02   2.94E+02   1.37E+02   5.43E+01
CUM. (GR/ACF) SMALLER THAN D50        1.17E-01   1.00E-01   8.42E-02   7.41E-02   6.37E-02   2.98E-02   1.18E-02
CUM. (GR/DNCF) SMALLER THAN D50       2.37E-01   2.03E-01   1.70E-01   1.49E-01   1.29E-01   6.01E-02   2.37E-02
GEO. MEAN DIA. (MICROMETERS)          2.31E+01   5.44E+00   3.08E+00   1.84E+00   1.20E+00   6.17E-01   3.31E-01             4.03E-02
DM/DLOGD (MG/DNCM)                    2.36E+02   3.29E+02   3.03E+02   2.43E+02   2.71E+02   4.00E+02   5.82E+02             1.83E+02
DN/DLOGD (NO. PARTICLES/DNCM)         1.99E+07   2.12E+09   1.07E+10   4.03E+10   1.63E+11   1.77E+12   1.67E+13             2.90E+15


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                         0.322      0.322      0.346      0.354      0.297      0.337      0.226
  HOLE DIAMETERS BY STAGE (CENTIMETERS)                0.3560     0.2461     0.1778     0.1368     0.0937     0.0739     0.0550
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KCCI-7  1-14-77  PORT-2  1252                                  INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - A

IMPACTOR FLOWRATE = 0.083 ACFM            IMPACTOR TEMPERATURE =  450.0 F = 232.2 C             SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 2.3 IN. OF HG      STACK TEMPERATURE =  450.0 F = 232.2 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)           CO2 =  6.55           CO =  0.00           N2 = 77.36           O2 =  8.30           H2O =  7.80

CALC. MASS LOADING = 3.6300E-01 GR/ACF             7.1684E-01 GR/DNCF              8.3067E+02 MG/ACM            1.6404E+03 MG/DNCM

IMPACTOR STAGE                              CYC       S0        S1        S2        S3        S4        S5                FILTER

STAGE INDEX NUMBER                           1         2         3         4         5         6         7                  8

D50 (MICROMETERS)                           8.13      4.67      2.57      1.65      1.09      0.34      0.28

MASS (MILLIGRAMS)                          28.90      7.30      8.46      3.18      2.28      3.18      3.16                2.11

MG/DNCM/STAGE                             8.20E+02  2.07E+02  2.40E+02  9.03E+01  6.47E+01  9.03E+01  8.97E+01            5.99E+01

CUM. PERCENT OF MASS SMALLER THAN D50  50.66     38.19     23.75     18.32     14.43      9.00      3.60

CUM. (MG/ACM) SMALLER THAN D50            4.21E+02  3.17E+02  1.97E+02  1.52E+02  1.20E+02  7.47E+01  2.99E+01

CUM. (MG/DNCM) SMALLER THAN D50           8.31E+02  6.27E+02  3.90E+02  3.01E+02  2.37E+02  1.48E+02  5.91E+01

CUM. (GR/ACF) SMALLER THAN D50            1.84E-01  1.39E-01  8.62E-02  6.65E-02  5.24E-02  3.27E-02  1.31E-02

CUM. (GR/DNCF) SMALLER THAN D50           3.63E-01  2.74E-01  1.70E-01  1.31E-01  1.03E-01  6.45E-02  2.58E-02

GEO. MEAN DIA. (MICROMETERS)              2.46E+01  6.16E+00  3.46E+00  2.06E+00  1.34E+00  6.11E-01  3.12E-01            6.03E-02

DM/DLOGD (MG/DNCM)                        8.53E+02  8.61E+02  9.23E+02  4.70E+02  3.58E+02  1.80E+02  1.06E+03            1.99E+02

DN/DLOGD (NO. PARTICLES/DNCM)             5.95E+07  3.82E+09  2.31E+10  5.60E+10  1.55E+11  8.20E+11  3.63E+13            9.40E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

  SQUARE ROOTS OF PSI BY STAGE                        0.322     0.322     0.338     0.345     0.258     0.317     0.229

  HOLE DIAMETERS BY STAGE (CENTIMETERS)               0.3554    0.2422    0.1779    0.1364    0.0884    0.0705    0.0556
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KCCI-A  1-14-77  PORT-2  1409                                   INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER = C

IMPACTOR FLOWRATE = 0.073 ALFM            IMPACTOR TEMPERATURE =  450.0 F = 232.2 C             SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 1.8 IN. OF HG       STACK TEMPERATURE =  450.0 F = 232.2 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.87 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)          CO2 =  6.55          CO =  0.00           N2 = 77.36           O2 =  8.30            H2O =  7.80

CALC. MASS LOADING = 1.6031E-01 GR/ACF             3.1647E-01 GR/DNCF            3.6685E+02 MG/ACM              7.2419E+02 MG/DNCM

IMPACTOR STAGE                          CYC        S0         S1         S2         S3         S4         S5                  FILTER

STAGE INDEX NUMBER                       1          2          3          4          5          6          7                     8

D50 (MICROMETERS)                       8.67       5.22       2.81       1.75       1.32       0.53       0.37

MASS (MILLIGRAMS)                       7.90       1.18       2.30       3.06       1.08       1.76       2.90                  2.57

MG/DNCM/STAGE                           2.55E+02   3.81E+01   7.42E+01   9.87E+01   3.48E+01   5.68E+01   9.36E+01              8.29E+01

CUM. PERCENT OF MASS SMALLER THAN D50  65.27      60.09      49.98      36.53      31.78      24.04      11.30

CUM. (MG/ACM) SMALLER THAN D50          2.39E+02   2.20E+02   1.83E+02   1.34E+02   1.17E+02   8.82E+01   4.14E+01

CUM. (MG/DNCM) SMALLER THAN D50         4.73E+02   4.35E+02   3.62E+02   2.65E+02   2.30E+02   1.74E+02   8.18E+01

CUM. (GR/ACF) SMALLER THAN D50          1.05E-01   9.63E-02   8.01E-02   5.86E-02   5.09E-02   3.85E-02   1.81E-02

CUM. (GR/DNCF) SMALLER THAN D50         2.07E-01   1.90E-01   1.58E-01   1.16E-01   1.01E-01   7.61E-02   3.58E-02

GEO. MEAN DIA. (MICROMETERS)            2.54E+01   6.73E+00   3.83E+00   2.22E+00   1.52E+00   8.37E-01   4.43E-01              1.09E-01

DM/DLOGD (MG/DNCM)                      2.73E+02   1.73E+02   2.77E+02   4.79E+02   2.88E+02   1.43E+02   6.03E+02              2.75E+02

DN/DLOGD (NO. PARTICLES/DNCM)           1.73E+07   5.89E+08   5.11E+09   4.55E+10   8.48E+10   2.52E+11   7.21E+12              2.24E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

 SQUARE ROOTS OF PSI BY STAGE                      0.322      0.322      0.351      0.388      0.330      0.350      0.273

 HOLE DIAMETERS BY STAGE (CENTIMETERS)             0.3658     0.2460     0.1724     0.1360     0.0896     0.0719     0.0589
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KCCI-10 1-15-77  PORT-2  1315                                 INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - C

IMPACTOR FLOWRATE = 0.083 ACFM           IMPACTOR TEMPERATURE =  450.0 F = 232.2 C              SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 2.3 IN. OF HG       STACK TEMPERATURE =  450.0 F = 232.2 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.87 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)           CO2 =  9.43          CO =  0.00           N2 = 76.55          O2 =  4.72           H2O =  9.30

CALC. MASS LOADING = 3.1218E-01 GR/ACF              6.2645E-01 GR/DNCF              7.1438E+02 MG/ACM              1.4335E+03 MG/DNCM

IMPACTOR STAGE                              CYC       S0        S1        S2        S3        S4        S5                 FILTER

STAGE INDEX NUMBER                           1         2         3         4         5         6         7                   8

D50 (MICROMETERS)                          8.08      4.86      2.62      1.62      1.23      0.49      0.34

MASS (MILLIGRAMS)                         23.76      5.58      2.86      3.70      2.60      5.30      3.74                2.83

MG/DNCM/STAGE                           6.85E+02  1.61E+02  8.25E+01  1.07E+02  7.50E+01  1.53E+02  1.08E+02            8.16E+01

CUM. PERCENT OF MASS SMALLER THAN D50   52.83     41.75     36.07     28.73     23.57     13.04      5.62

CUM. (MG/ACM) SMALLER THAN D50          3.77E+02  2.98E+02  2.58E+02  2.05E+02  1.68E+02  9.32E+01  4.01E+01

CUM. (MG/DNCM) SMALLER THAN D50         7.57E+02  5.99E+02  5.17E+02  4.12E+02  3.38E+02  1.87E+02  8.05E+01

CUM. (GR/ACF) SMALLER THAN D50          1.65E-01  1.30E-01  1.13E-01  8.97E-02  7.36E-02  4.07E-02  1.75E-02

CUM. (GR/DNCF) SMALLER THAN D50         3.31E-01  2.62E-01  2.26E-01  1.80E-01  1.48E-01  8.17E-02  3.52E-02

GEO. MEAN DIA. (MICROMETERS)            2.45E+01  6.26E+00  3.56E+00  2.06E+00  1.41E+00  7.72E-01  4.05E-01            9.47E-02

DM/DLOGD (MG/DNCM)                      7.11E+02  7.28E+02  3.07E+02  5.16E+02  6.17E+02  3.80E+02  6.81E+02            2.71E+02

DN/DLOGD (NO. PARTICLES/DNCM)           5.01E+07  3.07E+09  7.04E+09  6.11E+10  2.28E+11  8.56E+11  1.06E+13            3.31E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

  SQUARE ROOTS OF PSI BY STAGE                    0.322     0.322     0.351     0.388     0.330     0.350     0.273

  HOLE DIAMETERS BY STAGE (CENTIMETERS)           0.3658    0.2460    0.1724    0.1360    0.0896    0.0719    0.0589
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KCCI-11 1-15-77  PORT-2  1357                                        INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - D

IMPACTOR FLOWRATE = 0.966 ACFM             IMPACTOR TEMPERATURE =  476.0 F = 246.7 C                SAMPLING DURATION =  30.00 MIN

IMPACTOR PRESSURE DROP = 2.4 IN. OF HG       STACK TEMPERATURE =  476.0 F = 246.7 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS

GAS COMPOSITION (PERCENT)          CO2 =  9.43          CO =  0.00          N2 = 76.55          O2 =  4.72          H2O =  9.30

CALC. MASS LOADING = 4.4437E-01 GR/ACF              9.1754E-01 GR/DNCF              1.0169E+03 MG/ACM              2.0996E+03 MG/DNCM

IMPACTOR STAGE                            CYC       S0        S1        S2        S3        S4        S5                  FILTER

STAGE INDEX NUMBER                         1         2         3         4         5         6         7                    8

D50 (MICROMETERS)                         8.02      4.62      2.59      1.66      1.11      0.45      0.33

MASS (MILLIGRAMS)                        41.98      6.60      8.76      2.84      1.94      5.84      3.46                 2.87

MG/DNCM/STAGE                           1.20E+03  1.89E+02  2.51E+02  8.14E+01  5.56E+01  1.67E+02  9.91E+01             8.22E+01

CUM. PERCENT OF MASS SMALLER THAN D50   43.49     34.61     22.82     18.99     16.38      8.52      3.86

CUM. (MG/ACM) SMALLER THAN D50          4.42E+02  3.52E+02  2.32E+02  1.93E+02  1.67E+02  8.66E+01  3.93E+01

CUM. (MG/DNCM) SMALLER THAN D50         9.13E+02  7.27E+02  4.79E+02  3.99E+02  3.44E+02  1.79E+02  8.11E+01

CUM. (GR/ACF) SMALLER THAN D50          1.93E-01  1.54E-01  1.01E-01  8.44E-02  7.28E-02  3.79E-02  1.72E-02

CUM. (GR/DNCF) SMALLER THAN D50         3.99E-01  3.18E-01  2.09E-01  1.74E-01  1.50E-01  7.82E-02  3.54E-02

GEO. MEAN DIA. (MICROMETERS)            2.44E+01  6.09E+00  3.46E+00  2.08E+00  1.36E+00  7.08E-01  3.87E-01             5.46E-02

DM/DLOGD (MG/DNCM)                      1.24E+03  7.88E+02  1.00E+03  4.22E+02  3.13E+02  4.33E+02  7.22E+02             2.73E+02

DN/DLOGD (NO. PARTICLES/DNCM)           8.85E+07  3.63E+09  2.51E+10  4.89E+10  1.31E+11  1.26E+12  1.29E+13             1.74E+15


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

 SQUARE ROOTS OF PSI BY STAGE                     0.322     0.322     0.346     0.354     0.297     0.337     0.226

 HOLE DIAMETERS BY STAGE (CENTIMETERS)            0.3560    0.2461    0.1778    0.1368    0.0937    0.0739    0.0550
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KCCI-12 1-15-77  PORT-2  1448                                        INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - A

IMPACTOR FLOWRATE = 0,081 ACFM                  IMPACTOR TEMPERATURE =  476,0 F = 246,7 C             SAMPLING DURATION =  30,00 MIN

IMPACTOR PRESSURE DROP = 2,1 IN, OF HG          STACK TEMPERATURE =  476,0 F = 246,7 C

ASSUMED PARTICLE DENSITY = 1,84 GM/CU,CM,       STACK PRESSURE = 27,86 IN, OF HG     MAX, PARTICLE DIAMETER =   74,4 MICROMETERS

GAS COMPOSITION (PERCENT)            CO2 =  9,43         CO =  0,00          N2 = 76,55          O2 =  4,72            H2O =  9,30

CALC, MASS LOADING = 1,4994E-01 GR/ACF            3,0960E-01 GR/DNCF            3,4312E+02 MG/ACM            7,0848E+02 MG/DNCM

IMPACTOR STAGE                             CYC        S0        S1        S2        S3        S4        S5                 FILTER

STAGE INDEX NUMBER                          1          2         3         4         5         6         7                    8

D50 (MICROMETERS)                          8,27      4,75      2,61      1,68      1,11      0,35      0,29

MASS (MILLIGRAMS)                          1,80      4,78      5,64      1,96      2,06      2,60      2,78                 1,99

MG/DNCM/STAGE                           5,47E+01  1,45E+02  1,72E+02  5,96E+01  6,27E+01  7,91E+01  8,46E+01             6,05E+01

CUM, PERCENT OF MASS SMALLER THAN D50  92,38     72,13     48,24     39,94     31,22     20,20      8,43

CUM, (MG/ACM) SMALLER THAN D50          3,17E+02  2,47E+02  1,66E+02  1,37E+02  1,07E+02  6,93E+01  2,89E+01

CUM, (MG/DNCM) SMALLER THAN D50         6,54E+02  5,11E+02  3,42E+02  2,83E+02  2,21E+02  1,43E+02  5,97E+01

CUM, (GR/ACF) SMALLER THAN D50          1,39E-01  1,08E-01  7,23E-02  5,99E-02  4,68E-02  3,03E-02  1,26E-02

CUM, (GR/DNCF) SMALLER THAN D50         2,86E-01  2,23E-01  1,49E-01  1,24E-01  9,66E-02  6,26E-02  2,61E-02

GEO, MEAN DIA, (MICROMETERS)            2,48E+01  6,27E+00  3,52E+00  2,09E+00  1,36E+00  6,21E-01  3,17E-01             6,18E-02

DM/DLOGD (MG/DNCM)                      5,74E+01  6,04E+02  6,59E+02  3,10E+02  3,46E+02  1,58E+02  1,00E+03             2,01E+02

DN/DLOGD (NO, PARTICLES/DNCM)           3,90E+06  2,55E+09  1,57E+10  3,52E+10  1,43E+11  6,84E+11  3,27E+13             8,84E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG,

  SQUARE ROOTS OF PSI BY STAGE                       0,322     0,322     0,338     0,345     0,258     0,317     0,229

  HOLE DIAMETERS BY STAGE (CENTIMETERS)              0,3554    0,2422    0,1779    0,1364    0,0884    0,0705    0,0556
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KCCI-14 1-16-77  PORT-2  1255                                    INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER = C
IMPACTOR FLOWRATE = 0.368 ACFM              IMPACTOR TEMPERATURE =  476.0 F = 246.7 C                SAMPLING DURATION =  30.00 MIN
IMPACTOR PRESSURE DROP = 1.5 IN. OF HG      STACK TEMPERATURE =  476.0 F = 246.7 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  8.49          CO =  0.00          N2 = 75.22          O2 =  6.59          H2O =  9.70
CALC. MASS LOADING = 4.6350E-01 GR/ACF            9.6129E-01 GR/DNCF             1.0606E+03 MG/ACM            2.1997E+03 MG/DNCM
IMPACTOR STAGE                            CYC        S0        S1        S2        S3        S4        S5                 FILTER
STAGE INDEX NUMBER                         1          2         3         4         5         6         7                    8
D50 (MICROMETERS)                        9.03       5.44      2.93      1.83      1.38      0.55      0.39
MASS (MILLIGRAMS)                       32.71       5.99      6.97      1.33      3.40      5.65      5.01                 0.21
MG/DNCM/STAGE                         1.19E+03  2.18E+02  2.54E+02  4.84E+01  1.24E+02  2.06E+02  1.82E+02             7.64E+00
CUM. PERCENT OF MASS SMALLER THAN D50  46.61     36.84     25.46     23.29     17.74      8.52      0.34
CUM. (MG/ACM) SMALLER THAN D50        4.94E+02  3.91E+02  2.70E+02  2.47E+02  1.88E+02  9.04E+01  3.64E+00
CUM. (MG/DNCM) SMALLER THAN D50       1.03E+03  8.10E+02  5.60E+02  5.12E+02  3.90E+02  1.87E+02  7.54E+00
CUM. (GR/ACF) SMALLER THAN D50        2.16E-01  1.71E-01  1.18E-01  1.08E-01  8.22E-02  3.95E-02  1.59E-03
CUM. (GR/DNCF) SMALLER THAN D50       4.48E-01  3.54E-01  2.45E-01  2.24E-01  1.71E-01  8.19E-02  3.29E-03
GEO. MEAN DIA. (MICROMETERS)          2.59E+01  7.01E+00  4.00E+00  2.31E+00  1.59E+00  8.75E-01  4.64E-01             1.16E-01
DM/DLOGD (MG/DNCM)                    1.30E+03  9.90E+02  9.47E+02  2.35E+02  1.02E+03  5.18E+02  1.18E+03             2.54E+01
DN/DLOGD (NO. PARTICLES/DNCM)         7.74E+07  2.98E+09  1.54E+10  1.96E+10  2.65E+11  8.01E+11  1.23E+13             1.69E+13

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
 SQUARE ROOTS OF PSI BY STAGE                     0.322     0.322     0.351     0.388     0.330     0.350     0.273
 HOLE DIAMETERS BY STAGE (CENTIMETERS)            0.3658    0.2460    0.1724    0.1360    0.0896    0.0719    0.0589
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KCCI-15 1-16-77  PORT-2  1341                                  INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER = A
IMPACTOR FLOWRATE = 0.086 ACFM                IMPACTOR TEMPERATURE =  470.0 F = 243.3 C                SAMPLING DURATION =  35.00 MIN
IMPACTOR PRESSURE DROP = 2.4 IN. OF HG        STACK TEMPERATURE =  470.0 F = 243.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.      STACK PRESSURE = 27.83 IN. OF HG      MAX. PARTICLE DIAMETER =   74.4 MICROMETERS
GAS COMPOSITION (PERCENT)           CO2 =  8.49           CO =  0.00           N2 = 75.22           O2 =  6.59           H2O =  9.70
CALC. MASS LOADING = 2.9486E-01 GR/ACF             6.0825E-01 GR/DNCF              6.7473E+02 MG/ACM              1.3919E+03 MG/DNCM
IMPACTOR STAGE                              CYC        S0        S1        S2        S3        S4        S5                FILTER
STAGE INDEX NUMBER                           1          2         3         4         5         6         7                  8
D50 (MICROMETERS)                          8.01       4.60      2.53      1.62      1.07      0.33      0.27
MASS (MILLIGRAMS)                         23.40       7.61     10.03      2.75      1.41      5.57      4.57                2.17
MG/DNCM/STAGE                          5.74E+02  1.87E+02  2.46E+02  6.75E+01  3.46E+01  1.37E+02  1.12E+02            5.32E+01
CUM. PERCENT OF MASS SMALLER THAN D50  59.31      46.08     28.64     23.86     21.40     11.72      3.77
CUM. (MG/ACM) SMALLER THAN D50         4.00E+02  3.11E+02  1.93E+02  1.61E+02  1.44E+02  7.91E+01  2.55E+01
CUM. (MG/DNCM) SMALLER THAN D50        8.26E+02  6.41E+02  3.99E+02  3.32E+02  2.98E+02  1.63E+02  5.25E+01
CUM. (GR/ACF) SMALLER THAN D50         1.75E-01  1.36E-01  8.44E-02  7.03E-02  6.31E-02  3.46E-02  1.11E-02
CUM. (GR/DNCF) SMALLER THAN D50        3.61E-01  2.80E-01  1.74E-01  1.45E-01  1.30E-01  7.13E-02  2.30E-02
GEO. MEAN DIA. (MICROMETERS)           2.44E+01  6.07E+00  3.41E+00  2.02E+00  1.32E+00  5.98E-01  3.03E-01            5.76E-02
DM/DLOGD (MG/DNCM)                     5.93E+02  7.75E+02  9.45E+02  3.51E+02  1.91E+02  2.71E+02  1.31E+03            1.77E+02
DN/DLOGD (NO. PARTICLES/DNCM)          4.23E+07  3.59E+09  2.48E+10  4.39E+10  8.69E+10  1.32E+12  4.87E+13            9.63E+14


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                      0.322     0.322     0.338     0.345     0.258     0.317     0.229
  HOLE DIAMETERS BY STAGE (CENTIMETERS)             0.3554    0.2422    0.1779    0.1364    0.0884    0.0705    0.0556
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KCCI-16 1-16-77  PORT-2  1440                                  INLET SAMPLE    MODIFIED BRINK CASCADE IMPACTOR NUMBER - D
IMPACTOR FLOWRATE = 0.092 ACFM              IMPACTOR TEMPERATURE =  470.0 F = 243.3 C                SAMPLING DURATION =  40.00 MIN
IMPACTOR PRESSURE DROP = 2.7 IN. OF HG      STACK TEMPERATURE =  470.0 F = 243.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.    STACK PRESSURE = 27.83 IN. OF HG     MAX. PARTICLE DIAMETER =   74.4 MICROMETERS
GAS COMPOSITION (PERCENT)           CO2 =  8.49          CO =  0.00            N2 = 75.22           O2 =  6.59            H2O =  9.70
CALC. MASS LOADING = 5.5007E-01 GR/ACF            1.1347E+00 GR/DNCF            1.2588E+03 MG/ACM             2.5967E+03 MG/DNCM
IMPACTOR STAGE                          CYC       S0        S1        S2        S3        S4        S5                  FILTER
STAGE INDEX NUMBER                       1         2         3         4         5         6         7                    8
D50 (MICROMETERS)                      7.75      4.45      2.50      1.60      1.06      0.43      0.31
MASS (MILLIGRAMS)                     80.92     17.37     11.29      2.39      5.39      7.31      3.03                  3.47
MG/DNCM/STAGE                       1.62E+03  3.49E+02  2.27E+02  4.80E+01  1.08E+02  1.47E+02  6.08E+01              6.96E+01
CUM. PERCENT OF MASS SMALLER THAN D50 38.31     25.07     16.46     14.64     10.53      4.96      2.65
CUM. (MG/ACM) SMALLER THAN D50      4.82E+02  3.16E+02  2.07E+02  1.84E+02  1.33E+02  6.24E+01  3.33E+01
CUM. (MG/DNCM) SMALLER THAN D50     9.95E+02  6.51E+02  4.27E+02  3.80E+02  2.73E+02  1.29E+02  6.87E+01
CUM. (GR/ACF) SMALLER THAN D50      2.11E-01  1.38E-01  9.05E-02  8.05E-02  5.79E-02  2.73E-02  1.46E-02
CUM. (GR/DNCF) SMALLER THAN D50     4.35E-01  2.84E-01  1.87E-01  1.66E-01  1.19E-01  5.62E-02  3.00E-02
GEO. MEAN DIA. (MICROMETERS)        2.40E+01  5.87E+00  3.34E+00  2.00E+00  1.30E+00  6.79E-01  3.70E-01              5.02E-02
DM/DLOGD (MG/DNCM)                  1.65E+03  1.45E+03  9.03E+02  2.48E+02  6.08E+02  3.77E+02  4.37E+02              2.31E+02
DN/DLOGD (NO. PARTICLES/DNCM)       1.24E+08  7.42E+09  2.52E+10  3.22E+10  2.84E+11  1.25E+12  8.98E+12              1.90E+15


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                0.322     0.322     0.346     0.354     0.297     0.337     0.226
  HOLE DIAMETERS BY STAGE (CENTIMETERS)       0.3560    0.2461    0.1778    0.1368    0.0937    0.0739    0.0550
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KCCO-1  1-12-77  PORT-5  1015                                   OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - C

IMPACTOR FLOWRATE = 0.393 ACFM               IMPACTOR TEMPERATURE =  335.0 F = 168.3 C              SAMPLING DURATION = 120.00 MIN

IMPACTOR PRESSURE DROP = 0.6 IN. OF HG       STACK TEMPERATURE =  335.0 F = 168.3 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS

GAS COMPOSITION (PERCENT)          CO2 =  6.47          CO =  0.00           N2 = 77.98           O2 =  8.05            H2O =  7.50

CALC. MASS LOADING = 9.6698E-03 GR/ACF            1.6627E-02 GR/DNCF             2.2128E+01 MG/ACM             3.8048E+01 MG/DNCM

IMPACTOR STAGE                                   S1         S2         S3         S4         S5         S6         S7      FILTER

STAGE INDEX NUMBER                               1          2          3          4          5          6          7          8

D50 (MICROMETERS)                             10.82      11.11       4.72       2.03       1.05       0.73       0.26

MASS (MILLIGRAMS)                              7.82       1.47       4.08       1.88       1.44       1.92       5.78       5.16

MG/DSCM/STAGE                               1.02E+01   1.92E+00   5.32E+00   2.45E+00   1.88E+00   2.51E+00   7.54E+00   6.73E+00

CUM. PERCENT OF MASS SMALLER THAN D50      73.54      68.56      54.75      48.39      43.52      37.02      17.46

CUM. (MG/ACM) SMALLER THAN D50              1.63E+01   1.52E+01   1.21E+01   1.07E+01   9.63E+00   8.19E+00   3.86E+00

CUM. (MG/DNCM) SMALLER THAN D50             2.80E+01   2.61E+01   2.08E+01   1.84E+01   1.66E+01   1.41E+01   6.64E+00

CUM. (GR/ACF) SMALLER THAN D50              7.11E-03   6.63E-03   5.29E-03   4.68E-03   4.21E-03   3.58E-03   1.69E-03

CUM. (GR/DNCF) SMALLER THAN D50             1.22E-02   1.14E-02   9.10E-03   8.05E-03   7.24E-03   6.16E-03   2.90E-03

GEO. MEAN DIA. (MICROMETERS)                1.23E+01   1.10E+01   7.24E+00   3.09E+00   1.46E+00   8.79E-01   4.40E-01   1.87E-01

DM/DLOGD (MG/DNCM)                          9.14E+01  -1.70E+02   1.43E+01   6.70E+00   6.61E+00   1.60E+01   1.70E+01   2.24E+01

DN/DLOGD (NO. PARTICLES/DNCM)               5.08E+07  -1.33E+08   3.92E+07   2.35E+08   2.20E+09   2.44E+10   2.07E+11   3.58E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

  SQUARE ROOTS OF PSI BY STAGE               0.144      0.330      0.371      0.320      0.295      0.363      0.312

  HOLE DIAMETERS BY STAGE (CENTIMETERS)      1.8237     0.5874     0.2459     0.0807     0.0532     0.0376     0.0260
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KCCO-2  1-12-77  PORT-4  1015
                                                                        OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - A
IMPACTOR FLOWRATE = 0.491 ACFM                           IMPACTOR TEMPERATURE =  335.0 F = 168.3 C                    SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 1.0 IN. OF HG                   STACK TEMPERATURE =  335.0 F = 168.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.                STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)                    CO2 =  6.47            CO =  0.00             N2 = 77.98            O2 =  8.05            H2O =  7.50
CALC. MASS LOADING = 5.5090E-03 GR/ACF                   9.4724E-03 GR/DNCF                1.2606E+01 MG/ACM                   2.1676E+01 MG/DNCM
IMPACTOR STAGE                                   S1        S2        S3        S4        S5        S6        S7     FILTER
STAGE INDEX NUMBER                                1         2         3         4         5         6         7         8
D50 (MICROMETERS)                               9.67      9.65      4.32      1.51      0.95      0.53      0.23
MASS (MILLIGRAMS)                               4.59      0.28      0.47      3.22      2.35      0.87      2.18      7.09
MG/DSCM/STAGE                                4.79E+00  2.92E-01  4.91E-01  3.36E+00  2.45E+00  9.08E-01  2.28E+00  7.40E+00
CUM. PERCENT OF MASS SMALLER THAN D50       78.19     76.86     74.63     59.33     48.17     44.04     33.68
CUM. (MG/ACM) SMALLER THAN D50               9.86E+00  9.69E+00  9.41E+00  7.48E+00  6.07E+00  5.55E+00  4.25E+00
CUM. (MG/DNCM) SMALLER THAN D50              1.69E+01  1.67E+01  1.62E+01  1.29E+01  1.04E+01  9.55E+00  7.30E+00
CUM. (GR/ACF) SMALLER THAN D50               4.31E-03  4.23E-03  4.11E-03  3.27E-03  2.65E-03  2.43E-03  1.86E-03
CUM. (GR/DNCF) SMALLER THAN D50              7.41E-03  7.28E-03  7.07E-03  5.62E-03  4.56E-03  4.17E-03  3.19E-03
GEO. MEAN DIA. (MICROMETERS)                 1.16E+01  9.66E+00  6.45E+00  2.55E+00  1.20E+00  7.12E-01  3.49E-01  1.62E-01
DM/DLOGD (MG/DNCM)                           2.98E+01  4.29E+02  1.40E+00  7.37E+00  1.22E+01  3.60E+00  6.22E+00  2.46E+01
DN/DLOGD (NO. PARTICLES/DNCM)                1.96E+07  4.94E+08  5.42E+06  4.60E+08  7.35E+09  1.04E+10  1.51E+11  6.00E+12

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                 0.144     0.330     0.371     0.271     0.308     0.373     0.349
  HOLE DIAMETERS BY STAGE (CENTIMETERS)       1.8237    0.5768    0.2501    0.0808    0.0524    0.0333    0.0245
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KCCO-3  1-12-77  PORT-5  1435
                                                            OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. = 8
IMPACTOR FLOWRATE = 0.924 ACFM                IMPACTOR TEMPERATURE =  350.0 F = 176.7 C               SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 0.7 IN. OF HG        STACK TEMPERATURE =  350.0 F = 176.7 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.86 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  6.47          CO =  0.00          N2 = 77.98          O2 =  8.05          H2O =  7.50
CALC. MASS LOADING = 6.6411E-03 GR/ACF             1.1635E-02 GR/DNCF             1.5197E+01 MG/ACM             2.6624E+01 MG/DNCM
IMPACTOR STAGE                                S1        S2        S3        S4        S5        S6        S7      FILTER
STAGE INDEX NUMBER                            1         2         3         4         5         6         7         8
D50 (MICROMETERS)                          10.49      9.65      4.56      1.95      0.99      0.54      0.43
MASS (MILLIGRAMS)                           0.73      1.52      7.54      4.27      2.04      3.79      0.52      1.47
MG/DSCM/STAGE                           9.00E-01  1.87E+00  9.30E+00  5.27E+00  2.52E+00  4.67E+00  6.41E-01  1.81E+00
CUM. PERCENT OF MASS SMALLER THAN D50     96.66     89.72     55.26     35.74     26.42      9.10      6.72
CUM. (MG/ACM) SMALLER THAN D50          1.47E+01  1.36E+01  8.40E+00  5.43E+00  4.01E+00  1.38E+00  1.02E+00
CUM. (MG/DNCM) SMALLER THAN D50         2.57E+01  2.39E+01  1.47E+01  9.52E+00  7.03E+00  2.42E+00  1.79E+00
CUM. (GR/ACF) SMALLER THAN D50          6.42E-03  5.96E-03  3.67E-03  2.37E-03  1.75E-03  6.04E-04  4.46E-04
CUM. (GR/DNCF) SMALLER THAN D50         1.12E-02  1.04E-02  6.43E-03  4.16E-03  3.07E-03  1.06E-03  7.82E-04
GEO. MEAN DIA. (MICROMETERS)            1.21E+01  1.01E+01  6.63E+00  2.99E+00  1.39E+00  7.35E-01  4.83E-01  3.03E-01
DM/DLOGD (MG/DNCM)                      7.19E+00  5.14E+01  2.86E+01  1.43E+01  8.53E+00  1.80E+01  6.14E+00  6.02E+00
DN/DLOGD (NO. PARTICLES/DNCM)           4.19E+06  5.24E+07  1.02E+08  5.57E+08  3.29E+09  4.71E+10  5.65E+10  2.25E+11

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE                0.144     0.300     0.371     0.322     0.313     0.340     0.337
  HOLE DIAMETERS BY STAGE (CENTIMETERS)       1.8237    0.5822    0.2458    0.0802    0.0504    0.0340    0.0323
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KCCO-6  1-14-77  PORT-4  1016                                      OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. = D
IMPACTOR FLOWRATE = 0.461 ACFM                IMPACTOR TEMPERATURE =  335.0 F = 168.3 C                SAMPLING DURATION = 135.00 MIN
IMPACTOR PRESSURE DROP = 0.8 IN. OF HG        STACK TEMPERATURE =  335.0 F = 168.3 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.      STACK PRESSURE = 27.93 IN. OF HG      MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)            CO2 =  6.55          CO =  0.00             N2 = 77.36            O2 =  8.40            H2O =  7.80
CALC. MASS LOADING = 9.4741E-03 GR/ACF               1.6302E-02 GR/DNCF                 2.1680E+01 MG/ACM                3.7305E+01 MG/DNCM
IMPACTOR STAGE                                   S1        S2        S3        S4        S5        S6        S7      FILTER
STAGE INDEX NUMBER                                1         2         3         4         5         6         7         8
D50 (MICROMETERS)                              9.98      9.90      4.49      1.81      0.94      0.57      0.21
MASS (MILLIGRAMS)                             15.39      4.85      5.76      1.86      1.27      5.79      0.76      2.56
MG/DSCM/STAGE                               1.52E+01  4.80E+00  5.70E+00  1.84E+00  1.26E+00  5.73E+00  7.52E-01  2.53E+00
CUM. PERCENT OF MASS SMALLER THAN D50        59.75     47.07     32.01     27.14     23.82      8.68      6.69
CUM. (MG/ACM) SMALLER THAN D50              1.30E+01  1.02E+01  6.94E+00  5.88E+00  5.16E+00  1.88E+00  1.45E+00
CUM. (MG/DNCM) SMALLER THAN D50             2.23E+01  1.76E+01  1.19E+01  1.01E+01  8.89E+00  3.24E+00  2.50E+00
CUM. (GR/ACF) SMALLER THAN D50              5.66E-03  4.46E-03  3.03E-03  2.57E-03  2.26E-03  8.23E-04  6.34E-04
CUM. (GR/DNCF) SMALLER THAN D50             9.74E-03  7.67E-03  5.22E-03  4.43E-03  3.88E-03  1.42E-03  1.09E-03
GEO. MEAN DIA. (MICROMETERS)                1.18E+01  9.94E+00  6.66E+00  2.85E+00  1.30E+00  7.34E-01  3.49E-01  1.50E-01
DM/DLOGD (MG/DNCM)                          1.03E+02  1.35E+03  1.66E+01  4.65E+00  4.42E+00  2.68E+01  1.74E+00  8.41E+00
DN/DLOGD (NO. PARTICLES/DNCM)               6.50E+07  1.43E+09  5.82E+07  2.09E+08  2.08E+09  7.05E+10  4.25E+10  2.57E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
 SQUARE ROOTS OF PSI BY STAGE                  0.144     0.330     0.371     0.319     0.321     0.389     0.354
 HOLE DIAMETERS BY STAGE (CENTIMETERS)        1.8237    0.5743    0.2512    0.0793    0.0495    0.0330    0.0229
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KCCO-7  1-14-77  PORT-5  1145                                              OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - C
IMPACTOR FLOWRATE = 0.462 ACFM                         IMPACTOR TEMPERATURE =  355.0 F = 179.4 C             SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 0.8 IN. OF HG                 STACK TEMPERATURE =  355.0 F = 179.4 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.               STACK PRESSURE = 27.93 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)               CO2 =  6.55             CO =  0.00            N2 = 77.36            O2 =  8.30             H2O =  7.80
CALC. MASS LOADING = 8.3099E-03 GR/ACF                     1.4659E-02 GR/DNCF                1.9016E+01 MG/ACM                  3.3545E+01 MG/DNCM
IMPACTOR STAGE                                     S1        S2        S3        S4        S5        S6        S7      FILTER
STAGE INDEX NUMBER                                 1         2         3         4         5         6         7         8
D50 (MICROMETERS)                               10.06     10.33      4.38      1.88      0.97      0.67      0.23
MASS (MILLIGRAMS)                                2.97      0.92      4.74      1.77      1.63      2.20      5.00     10.61
MG/DSCM/STAGE                                 3.38E+00  1.05E+00  5.40E+00  2.02E+00  1.86E+00  2.51E+00  5.70E+00  1.21E+01
CUM. PERCENT OF MASS SMALLER THAN D50          90.05     86.96     71.08     65.15     59.68     52.31     35.56
CUM. (MG/ACM) SMALLER THAN D50                1.71E+01  1.65E+01  1.35E+01  1.24E+01  1.13E+01  9.95E+00  6.76E+00
CUM. (MG/DNCM) SMALLER THAN D50               3.02E+01  2.92E+01  2.38E+01  2.19E+01  2.00E+01  1.75E+01  1.19E+01
CUM. (GR/ACF) SMALLER THAN D50                7.48E-03  7.23E-03  5.91E-03  5.41E-03  4.96E-03  4.35E-03  2.95E-03
CUM. (GR/DNCF) SMALLER THAN D50               1.32E-02  1.27E-02  1.04E-02  9.55E-03  8.75E-03  7.67E-03  5.21E-03
GEO. MEAN DIA. (MICROMETERS)                  1.19E+01  1.02E+01  6.72E+00  2.87E+00  1.35E+00  8.06E-01  3.95E-01  1.65E-01
DM/DLOGD (MG/DNCM)                            2.36E+01 -9.25E+01  1.45E+01  5.48E+00  6.47E+00  1.56E+01  1.24E+01  4.02E+01
DN/DLOGD (NO. PARTICLES/DNCM)                 1.46E+07 -9.06E+07  4.95E+07  2.42E+08  2.74E+09  3.10E+10  2.09E+11  9.28E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PST BY STAGE                  0.144     0.330     0.371     0.320     0.295     0.363     0.312
  HOLE DIAMETERS BY STAGE (CENTIMETERS)         1.8237    0.5874    0.2459    0.0807    0.0532    0.0376    0.0260
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KCCO-8  1-14-77  PORT-4  1145                                          OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - A
IMPACTOR FLOWRATE = 0.752 ACFM               IMPACTOR TEMPERATURE =  355.0 F = 179.4 C                 SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 2.2 IN. OF HG       STACK TEMPERATURE =  355.0 F = 179.4 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 27.93 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  6.55          CO =  0.00           N2 = 77.36          O2 =  8.30            H2O =  7.80
CALC. MASS LOADING = 6.3370E-03 GR/ACF              1.1179E-02 GR/DNCF             1.4501E+01 MG/ACM              2.5581E+01 MG/DNCM
IMPACTOR STAGE                                S1         S2         S3         S4         S5         S6         S7      FILTER
STAGE INDEX NUMBER                            1          2          3          4          5          6          7          8
D50 (MICROMETERS)                           7.86       7.84       3.49       1.21       0.75       0.40       0.16
MASS (MILLIGRAMS)                          13.52       1.57       4.61       2.27       0.94       2.30       4.20       7.67
MG/DSCM/STAGE                             9.45E+00   1.10E+00   3.22E+00   1.59E+00   6.57E-01   1.61E+00   2.94E+00   5.36E+00
CUM. PERCENT OF MASS SMALLER THAN D50     63.54      59.30      46.87      40.75      38.21      32.01      20.69
CUM. (MG/ACM) SMALLER THAN D50            9.21E+00   8.60E+00   6.80E+00   5.91E+00   5.54E+00   4.64E+00   3.00E+00
CUM. (MG/DNCM) SMALLER THAN D50           1.63E+01   1.52E+01   1.20E+01   1.04E+01   9.78E+00   8.19E+00   5.29E+00
CUM. (GR/ACF) SMALLER THAN D50            4.03E-03   3.76E-03   2.97E-03   2.58E-03   2.42E-03   2.03E-03   1.31E-03
CUM. (GR/DNCF) SMALLER THAN D50           7.10E-03   6.63E-03   5.24E-03   4.56E-03   4.27E-03   3.58E-03   2.31E-03
GEO. MEAN DIA. (MICROMETERS)              1.05E+01   7.85E+00   5.23E+00   2.05E+00   9.52E-01   5.48E-01   2.50E-01   1.10E-01
DM/DLOGD (MG/DNCM)                        3.77E+01   1.61E+03   9.18E+00   3.44E+00   3.18E+00   5.89E+00   7.19E+00   1.78E+01
DN/DLOGD (NO. PARTICLES/DNCM)             3.39E+07   3.45E+09   6.64E+07   4.12E+08   3.83E+09   3.72E+10   4.77E+11   1.37E+13


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
  SQUARE ROOTS OF PSI BY STAGE               0.144      0.330      0.371      0.271      0.308      0.373      0.349
  HOLE DIAMETERS BY STAGE (CENTIMETERS)      1.8237     0.5768     0.2501     0.0808     0.0524     0.0333     0.0245
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KCC0-9  1-15-77  PORT-4  1000                                     OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - C

IMPACTOR FLOWRATE = 0.860 ACFM             IMPACTOR TEMPERATURE =  345.0 F = 173.9 C              SAMPLING DURATION =  82.00 MIN

IMPACTOR PRESSURE DROP = 3.0 IN. OF HG     STACK TEMPERATURE =  345.0 F = 173.9 C

ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 28.13 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS

GAS COMPOSITION (PERCENT)          CO2 =  9.43          CO =  0.00          N2 = 76.55          O2 =  4.72          H2O =  9.30

CALC. MASS LOADING = 1.0477E-02 GR/ACF           1.8425E-02 GR/DNCF            2.3976E+01 MG/ACM            4.2164E+01 MG/DNCM

IMPACTOR STAGE                             S1        S2        S3        S4        S5        S6        S7      FILTER

STAGE INDEX NUMBER                          1         2         3         4         5         6         7         8

D50 (MICROMETERS)                         7.24      7.44      3.13      1.33      0.67      0.44      0.13

MASS (MILLIGRAMS)                         0.03      0.35      4.45      3.25      5.40     10.35     14.98      9.29

MG/DSCM/STAGE                          2.67E-02  3.11E-01  3.95E+00  2.89E+00  4.80E+00  9.20E+00  1.33E+01  8.25E+00

CUM. PERCENT OF MASS SMALLER THAN D50   99.94     99.21     89.96     83.20     71.98     50.46     19.31

CUM. (MG/ACM) SMALLER THAN D50         2.40E+01  2.38E+01  2.16E+01  1.99E+01  1.73E+01  1.21E+01  4.63E+00

CUM. (MG/DNCM) SMALLER THAN D50        4.21E+01  4.18E+01  3.79E+01  3.51E+01  3.03E+01  2.13E+01  8.14E+00

CUM. (GR/ACF) SMALLER THAN D50         1.05E-02  1.04E-02  9.43E-03  8.72E-03  7.54E-03  5.29E-03  2.02E-03

CUM. (GR/DNCF) SMALLER THAN D50        1.84E-02  1.83E-02  1.66E-02  1.53E-02  1.33E-02  9.30E-03  3.56E-03

GEO. MEAN DIA. (MICROMETERS)           1.01E+01  7.34E+00  4.83E+00  2.04E+00  9.44E-01  5.42E-01  2.39E-01  9.19E-02

DM/DLOGD (MG/DNCM)                     9.32E-02 -2.73E+01  1.05E+01  7.74E+00  1.62E+01  4.99E+01  2.52E+01  2.74E+01

DN/DLOGD (NO. PARTICLES/DNCM)          9.47E+04 -7.18E+07  9.72E+07  9.46E+08  2.00E+10  3.24E+11  1.92E+12  3.67E+13


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.

SQUARE ROOTS OF PSI BY STAGE              0.144     0.330     0.371     0.320     0.295     0.363     0.312

HOLE DIAMETERS BY STAGE (CENTIMETERS)     1.8237    0.5874    0.2459    0.0807    0.0532    0.0376    0.0260
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KCCO-10 1-15-77  PORT-5  1000                                  OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - D
IMPACTOR FLOWRATE = 0.585 ACFM              IMPACTOR TEMPERATURE =  345.0 F = 173.9 C              SAMPLING DURATION =  75.00 MIN
IMPACTOR PRESSURE DROP = 1.4 IN. OF HG      STACK TEMPERATURE =  345.0 F = 173.9 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 28.13 IN. OF HG     MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  9.43          CO =  0.00           N2 = 76.55           O2 =  4.72            H2O =  9.30
CALC. MASS LOADING = 1.3739E-02 GR/ACF          2.4161E-02 GR/DNCF             3.1439E+01 MG/ACM                5.5289E+01 MG/DNCM
IMPACTOR STAGE                               S1         S2         S3         S4         S5         S6         S7      FILTER
STAGE INDEX NUMBER                           1          2          3          4          5          6          7          8
D50 (MICROMETERS)                          8.83       8.76       3.96       1.59       0.82       0.49       0.17
MASS (MILLIGRAMS)                          0.41       4.64       2.86       0.06       2.98      14.42       3.56      10.13
MG/DSCM/STAGE                            5.88E-01   6.66E+00   4.10E+00   8.61E-02   4.28E+00   2.07E+01   5.11E+00   1.45E+01
CUM. PERCENT OF MASS SMALLER THAN D50     98.95      87.07      79.75      79.60      71.97      35.05      25.93
CUM. (MG/ACM) SMALLER THAN D50           3.11E+01   2.74E+01   2.51E+01   2.50E+01   2.26E+01   1.10E+01   8.15E+00
CUM. (MG/DNCM) SMALLER THAN D50          5.47E+01   4.81E+01   4.41E+01   4.40E+01   3.98E+01   1.94E+01   1.43E+01
CUM. (GR/ACF) SMALLER THAN D50           1.36E-02   1.20E-02   1.10E-02   1.09E-02   9.89E-03   4.82E-03   3.56E-03
CUM. (GR/DNCF) SMALLER THAN D50          2.39E-02   2.10E-02   1.93E-02   1.92E-02   1.74E-02   8.47E-03   6.27E-03
GEO. MEAN DIA. (MICROMETERS)             1.11E+01   8.79E+00   5.89E+00   2.51E+00   1.14E+00   6.35E-01   2.93E-01   1.23E-01
DM/DLOGD (MG/DNCM)                       2.94E+00   1.88E+03   1.19E+01   2.17E-01   1.49E+01   9.35E+01   1.13E+01   4.83E+01
DN/DLOGD (NO. PARTICLES/DNCM)            2.22E+06   2.86E+09   6.05E+07   1.42E+07   1.04E+10   3.79E+11   4.69E+11   2.69E+13


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
SQUARE ROOTS OF PSI BY STAGE               0.144      0.330      0.371      0.319      0.321      0.389      0.354
HOLE DIAMETERS BY STAGE (CENTIMETERS)     1.8237     0.5743     0.2512     0.0793     0.0495     0.0330     0.0229
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KCCO-11 1-15-77  PORT-4  1410                                        OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - A
IMPACTOR FLOWRATE = 0.519 ACFM                    IMPACTOR TEMPERATURE =  365.0 F = 185.0 C               SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 1.0 IN. OF HG           STACK TEMPERATURE =  365.0 F = 185.0 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.          STACK PRESSURE = 28.13 IN. OF HG      MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)            CO2 =  9.43           CO =  0.00            N2 = 76.55            O2 =  4.72             H2O =  9.30
CALC. MASS LOADING = 1.2456E-02 GR/ACF                2.2450E-02 GR/DNCF               2.8504E+01 MG/ACM                5.1474E+01 MG/DNCM
IMPACTOR STAGE                                 S1        S2        S3        S4        S5        S6        S7      FILTER
STAGE INDEX NUMBER                              1         2         3         4         5         6         7         8
D50 (MICROMETERS)                             9.47      9.45      4.22      1.48      0.93      0.52      0.22
MASS (MILLIGRAMS)                             7.96      1.10      5.96      5.27      3.63      6.92     10.20      9.20
MG/DSCM/STAGE                              8.25E+00  1.14E+00  6.18E+00  5.46E+00  3.76E+00  7.17E+00  1.06E+01  9.54E+00
CUM. PERCENT OF MASS SMALLER THAN D50        84.16     81.97     70.10     59.61     52.39     38.61     18.31
CUM. (MG/ACM) SMALLER THAN D50             2.40E+01  2.34E+01  2.00E+01  1.70E+01  1.49E+01  1.10E+01  5.22E+00
CUM. (MG/DNCM) SMALLER THAN D50            4.32E+01  4.21E+01  3.60E+01  3.06E+01  2.69E+01  1.98E+01  9.41E+00
CUM. (GR/ACF) SMALLER THAN D50             1.05E-02  1.02E-02  8.73E-03  7.43E-03  6.53E-03  4.81E-03  2.28E-03
CUM. (GR/DNCF) SMALLER THAN D50            1.89E-02  1.84E-02  1.57E-02  1.34E-02  1.18E-02  8.67E-03  4.11E-03
GEO. MEAN DIA. (MICROMETERS)               1.15E+01  9.46E+00  6.32E+00  2.50E+00  1.17E+00  6.92E-01  3.37E-01  1.55E-01
DM/DLOGD (MG/DNCM)                         4.86E+01  1.67E+03  1.77E+01  1.20E+01  1.86E+01  2.82E+01  2.85E+01  3.17E+01
DN/DLOGD (NO. PARTICLES/DNCM)              3.30E+07  2.05E+09  7.26E+07  7.97E+08  1.21E+10  8.83E+10  7.73E+11  8.76E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
SQUARE ROOTS OF PSI BY STAGE                  0.144     0.330     0.371     0.271     0.308     0.373     0.349
HOLE DIAMETERS BY STAGE (CENTIMETERS)        1.8237    0.5768    0.2501    0.0808    0.0524    0.0333    0.0245
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KCCO-13 1-16-77  PORT-4  0915                                                OUTLET SAMPLE   U, OF W, MARK III SOURCE TEST IMPACTOR NO, = A

IMPACTOR FLOWRATE = 0,515 ACFM              IMPACTOR TEMPERATURE =  345,0 F = 173,9 C                SAMPLING DURATION = 120,00 MIN

IMPACTOR PRESSURE DROP = 0,4 IN, OF HG       STACK TEMPERATURE =  345,0 F = 173,9 C

ASSUMED PARTICLE DENSITY = 1,84 GM/CU,CM,      STACK PRESSURE = 28,13 IN, OF HG     MAX, PARTICLE DIAMETER =   14,0 MICROMETERS

GAS COMPOSITION (PERCENT)          CO2 =  8,49          CO =  0,00          N2 =  7,97          O2 =  6,59          H2O =  9,70

CALC, MASS LOADING = 1,5550E-02 GR/ACF            2,7467E-02 GR/DNCF             3,5583E+01 MG/ACM             6,2854E+01 MG/DNCM

IMPACTOR STAGE                            S1        S2        S3        S4        S5        S6        S7      FILTER

STAGE INDEX NUMBER                         1         2         3         4         5         6         7         8

D50 (MICROMETERS)                        9,11      9,09      4,02      1,36      0,83      0,44      0,17

MASS (MILLIGRAMS)                       22,67      3,79     14,89      6,34      1,74      3,83      5,69      3,32

MG/DSCM/STAGE                         2,32E+01  3,88E+00  1,52E+01  6,49E+00  1,78E+00  3,92E+00  5,82E+00  3,40E+00

CUM, PERCENT OF MASS SMALLER THAN D50   63,59     57,51     33,60     23,41     20,62     14,47      5,33

CUM, (MG/ACM) SMALLER THAN D50        2,26E+01  2,05E+01  1,20E+01  8,33E+00  7,34E+00  5,15E+00  1,90E+00

CUM, (MG/DNCM) SMALLER THAN D50       4,00E+01  3,61E+01  2,11E+01  1,47E+01  1,30E+01  9,09E+00  3,35E+00

CUM, (GR/ACF) SMALLER THAN D50        9,89E-03  8,94E-03  5,22E-03  3,64E-03  3,21E-03  2,25E-03  8,29E-04

CUM, (GR/DNCF) SMALLER THAN D50       1,75E-02  1,58E-02  9,23E-03  6,43E-03  5,66E-03  3,97E-03  1,46E-03

GEO, MEAN DIA, (MICROMETERS)          1,13E+01  9,10E+00  6,05E+00  2,34E+00  1,06E+00  6,04E-01  2,71E-01  1,18E-01

DM/DLOGD (MG/DNCM)                    1,24E+02  5,63E+03  4,30E+01  1,38E+01  8,30E+00  1,41E+01  1,39E+01  1,13E+01

DN/DLOGD (NO, PARTICLES/DNCM)         8,96E+07  7,76E+09  2,02E+08  1,12E+09  7,16E+09  6,67E+10  7,27E+11  7,11E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG,

 SQUARE ROOTS OF PSI BY STAGE           0,144     0,330     0,371     0,271     0,308     0,373     0,349

 HOLE DIAMETERS BY STAGE (CENTIMETERS)  1,8237    0,5768    0,2501    0,0808    0,0524    0,0333    0,0245
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KCCO-15 1-16-77  PORT-4  1345                                     OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. = C
IMPACTOR FLOWRATE = 0.508 ACFM               IMPACTOR TEMPERATURE =  350,0 F = 176,7 C               SAMPLING DURATION = 120,00 MIN
IMPACTOR PRESSURE DROP = 0.3 IN. OF HG       STACK TEMPERATURE =  350,0 F = 176,7 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.     STACK PRESSURE = 28.13 IN. OF HG     MAX. PARTICLE DIAMETER =   14,0 MICROMETERS
GAS COMPOSITION (PERCENT)           CO2 =  8,49           CO =  0,00            N2 =  7,97           O2 =  6,59           H2O =  9,70
CALC. MASS LOADING = 4.2665E-03 GR/ACF            7.5832E-03 GR/DNCF            9,7633E+00 MG/ACM            1,7353E+01 MG/DNCM
IMPACTOR STAGE                                  S1         S2         S3         S4         S5         S6         S7      FILTER
STAGE INDEX NUMBER                              1          2          3          4          5          6          7          8
D50 (MICROMETERS)                             9,20       9,44       3,96       1,65       0,82       0,55       0,16
MASS (MILLIGRAMS)                             4,82       0,73       3,60       0,90       0,50       0,95       4,18       1,17
MG/DSCM/STAGE                              5,03E+00  7,62E-01  3,76E+00  9,39E-01  5,22E-01  9,92E-01  4,36E+00  1,22E+00
CUM. PERCENT OF MASS SMALLER THAN D50    71,39      67,06      45,70      40,36      37,39      31,75      6,94
CUM. (MG/ACM) SMALLER THAN D50             6,97E+00  6,55E+00  4,46E+00  3,94E+00  3,65E+00  3,10E+00  6,78E-01
CUM. (MG/DNCM) SMALLER THAN D50            1,24E+01  1,16E+01  7,93E+00  7,00E+00  6,49E+00  5,51E+00  1,20E+00
CUM. (GR/ACF) SMALLER THAN D50             3,05E-03  2,86E-03  1,95E-03  1,72E-03  1,60E-03  1,35E-03  2,96E-04
CUM. (GR/DNCF) SMALLER THAN D50            5,41E-03  5,09E-03  3,47E-03  3,06E-03  2,84E-03  2,41E-03  5,27E-04
GEO. MEAN DIA. (MICROMETERS)               1,13E+01  9,32E+00  6,11E+00  2,56E+00  1,16E+00  6,69E-01  2,98E-01  1,15E-01
DM/DLOGD (MG/DNCM)                         2,76E+01 -6,67E+01  9,95E+00  2,48E+00  1,71E+00  5,66E+00  8,28E+00  4,06E+00
DN/DLOGD (NO. PARTICLES/DNCM)              1,96E+07 -8,56E+07  4,52E+07  1,54E+08  1,13E+09  1,96E+10  3,25E+11  2,78E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
 SQUARE ROOTS OF PSI BY STAGE                  0,144      0,330      0,371      0,320      0,295      0,363      0,312
 HOLE DIAMETERS BY STAGE (CENTIMETERS)         1,8237     0,5874     0,2459     0,0807     0,0532     0,0376     0,0260
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KCCU-16 1-16-77  PORI-5  1345                                            OUTLET SAMPLE   U. OF W. MARK III SOURCE TEST IMPACTOR NO. - D
IMPACTOR FLOWRATE = 0.469 ACFM                       IMPACTOR TEMPERATURE =  350.0 F = 176.7 C              SAMPLING DURATION = 120.00 MIN
IMPACTOR PRESSURE DROP = 0.3 IN. OF HG               STACK TEMPERATURE =  350.0 F = 176.7 C
ASSUMED PARTICLE DENSITY = 1.84 GM/CU.CM.             STACK PRESSURE = 28.13 IN. OF HG      MAX. PARTICLE DIAMETER =   14.0 MICROMETERS
GAS COMPOSITION (PERCENT)            CO2 =  8.49            CO =  0.00             N2 =  7.97            O2 =  6.59              H2O =  9.70
CALC. MASS LOADING = 5.1644E-03 GR/ACF                  9.1791E-03 GR/DNCF                 1.1818E+01 MG/ACM                2.1005E+01 MG/DNCM
IMPACTOR STAGE                                 S1         S2         S3         S4         S5         S6         S7       FILTER
STAGE INDEX NUMBER                              1          2          3          4          5          6          7          8
D50 (MICROMETERS)                             9.57       9.50       4.26       1.67       0.83       0.49       0.16
MASS (MILLIGRAMS)                             6.73       1.03       3.61       0.89       0.35       1.37       2.83       2.04
MG/DSCM/STAGE                              7.60E+00   1.16E+00   4.08E+00   1.01E+00   3.95E-01   1.55E+00   3.20E+00   2.30E+00
CUM. PERCENT OF MASS SMALLER THAN D50     64.30      58.83      39.68      34.96      33.10      25.84      10.82
CUM. (MG/ACM) SMALLER THAN D50             7.60E+00   6.95E+00   4.69E+00   4.13E+00   3.91E+00   3.05E+00   1.28E+00
CUM. (MG/DNCM) SMALLER THAN D50            1.35E+01   1.24E+01   8.34E+00   7.34E+00   6.95E+00   5.43E+00   2.27E+00
CUM. (GR/ACF) SMALLER THAN D50             3.32E-03   3.04E-03   2.05E-03   1.81E-03   1.71E-03   1.33E-03   5.59E-04
CUM. (GR/DNCF) SMALLER THAN D50            5.90E-03   5.40E-03   3.64E-03   3.21E-03   3.04E-03   2.37E-03   9.93E-04
GEO. MEAN DIA. (MICROMETERS)               1.16E+01   9.53E+00   6.36E+00   2.67E+00   1.18E+00   6.37E-01   2.76E-01   1.10E-01
DM/DLOGD (MG/DNCM)                         4.61E+01   3.25E+02   1.17E+01   2.47E+00   1.31E+00   6.61E+00   6.48E+00   7.65E+00
DN/DLOGD (NO. PARTICLES/DNCM)              3.08E+07   3.90E+08   4.72E+07   1.35E+08   8.26E+08   2.65E+10   3.20E+11   5.89E+12


NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 21 DEG C AND 760MM HG.
 SQUARE ROOTS OF PSI BY STAGE                0.144      0.330      0.371      0.319      0.321      0.389      0.354
 HOLE DIAMETERS BY STAGE (CENTIMETERS)       1.8237     0.5743     0.2512     0.0793     0.0495     0.0330     0.0229
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